L. D. Kravchenko

TRANSFLUXORS

AND THEIR APPLICATION IN AUTOMATION AND REMOTE CONTROL

GPO PRICE $ _____

CFSTI PRICE(S) $ 3.00

Hard copy (HC) 3

Microfiche (MF) .75

ff 653 July 65

N66 36299
(ACCESSION NUMBER)

58
(PAGES)

(NASA CR OR TMX OR AD NUMBER)

(THRU)
1
(CODE)
09
(CATEGORY)

FACILITY FORM 602

TRANSLATED FROM RUSSIAN

Published for the National Aeronautics and Space Administration, U.S.A.

and the National Science Foundation, Washington, D.C.

by the Israel Program for Scientific Translations

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and Their Application in

Automation and Remote Control

(Transflyuksory v ustroistvakh teleupravleniya)

2nd edition

Izdatel'stvo "Tekhnika"
Kiev 1964

Translated from Russian

Israel Program for Scientific Translations
Jerusalem 1966

NASA TT F-347
TT 66-51032

Published Pursuant to an Agreement with
THE U.S. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
and
THE NATIONAL SCIENCE FOUNDATION, WASHINGTON, D.C.

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IPST Cat. No. 1534

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Printed in Jerusalem by S. Monson

Price: $3.00

Available from the
U.S. DEPARTMENT OF COMMERCE
Clearinghouse for Federal Scientific and Technical Information
Springfield, Va. 22151

V/13

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This booklet discusses the principles of operation of transfluxors, their design considerations, reliability, and application in automation, telemechanics, and computer technology.

It is intended for engineers engaged in the fields of automation and telemechanics.

INTRODUCTION

Automation and telemechanization of industrial processes is a means of increasing labor productivity. Many problems arise in telemechanization when attempting to design highly reliable and economical remote control and telemetering (RC-TM) systems. One method of solving these problems is to use noncontacting elements.

Noncontacting elements are devices lacking mechanical contacts for switching electrical currents. Such elements include electronic and gas-discharge devices, magnetic amplifiers, ferrites with a rectangular hysteresis loop, and others. Very little maintenance is necessary during operation of noncontacting elements and they can withstand vibrations and accelerations; their lifetime is longer than that of most reliable contacting elements.

Systems of RC-TM commonly use switching devices with one or two stable positions, corresponding to the maximum or minimum signal at the output of the device. One of the noncontacting switching elements most widely used in automation, telemechanization, and computing technology, are ferrite cores with a rectangular hysteresis loop (RHL).

At present there are several types of RC-TM systems consisting almost completely of these ferrite elements. The use of ferrite cores in core-transistor cells has many advantages, e.g., high signal to noise ratio, increased sensitivity to control signals and, consequently, drawing of less power from the control signal source.

A further development of ferrite elements are magnetic cores of complex configuration having several paths for the magnetic flux /5/. One such core, the transfluxor, can replace several simple elements.

All the possible uses of transfluxors have not yet been studied; however, to date, they can be successfully used as switches, triggers, in memory matrixes, and in logic, automation, and telemechanical systems.

The purpose of this booklet is to describe design methods and practical circuits using transfluxors. In this publication the author draws on his own works and other sources. The MKS system is used throughout.

Please send any comments to the following address: Kiev, 4, Pushkinskaya, 28, "Tekhnika" Publishing House.

The Author

Chapter I

TRANSFLUXOR DESIGN CONSIDERATIONS

Principle of operation of the transfluxor

The simplest transfluxor is a disk with two apertures (Figure 1a). The disk is of ferrite material with a rectangular hysteresis loop (Figure 2).

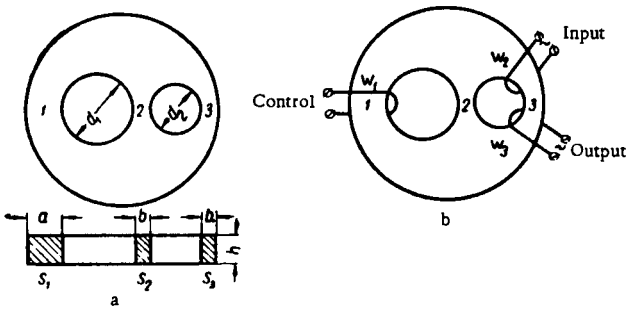

FIGURE 1. A two-apertured transfluxor:

a—outline drawings; b—typical circuit.

The diameters of the apertures are different. They are chosen according to the problem and have the following relationship:

$$d_1 = (1.5 - 5)d_2.$$

In a two-apertured transfluxor (Figure 1b) there are three possible paths for the magnetic flux: via legs 1, 2, and 3. The cross section of leg 1 is equal to or more than the sum of the cross sections of legs 2 and 3. The hysteresis loop of the ferrite is rectangular, therefore, we can fix the direction of magnetization in the various legs. This aperture arrangement enables a certain zone of any leg to be magnetized in one direction without changing the direction of magnetization in the neighboring leg.

A control winding, w_1, is placed on leg 1, and an a-c energizing winding, w_2, and an output winding, w_3, on leg 3.

Let us assume that a negative current pulse is fed to control winding w_1, the pulse having an amplitude sufficient to produce a saturation flux in leg 1. The flux divides and passes through legs 2 and 3. As the total cross sections of these legs are equal to the cross section of leg 1, legs 2 and 3 will also

be saturated. In the zone around the small aperture magnetizing will be in the same direction (Figure 3a).

Let us now connect the energizing winding w_2 to an a-c source having an amplitude sufficient only to reverse the magnetization of the zone around the small aperture. The diameter of this zone is equal to $d_2 + 2b$.

During the positive halfwave of the energizing current (Figure 3b) the direction of the flux in leg 3 is in the same direction and in leg 2 in the opposite direction to that of the magnetization, but no flux change will occur in the zone around the small aperture since this zone has already been saturated.

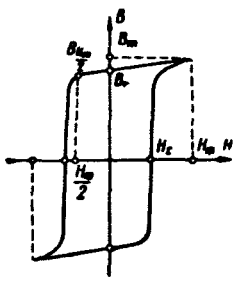

FIGURE 2. Rectangular hysteresis loop:

H_c—coercive force; H_m—maximum magnetic intensity; B_m—maximum induction; $B_{H_m/2}$—induction corresponding to half the maximum magnetic intensity; B_r—residual induction.

During the negative halfwave of the energizing current (Figure 3c) the direction of the flux will be the same as the magnetization in leg 2 and opposite to that in leg 3. Here, too, no flux change takes place around the small aperture. Due to the nonideal form of the hysteresis loop, a small alternating emf is induced in the output winding. This condition of the core is called closed or blocked.

When a negative pulse is fed to the control winding having an amplitude sufficient only to change the direction of magnetization in leg 2, a flux distributor as shown in Figure 3d is obtained. In this case, when the energizing current is positive, the flux in legs 2 and 3 will only bring the zone around the small aperture to a higher degree of saturation (Figure 3e).

When the energizing current is negative, the direction of magnetization around the small aperture is reversed and an emf of considerable magnitude is induced in the output winding (Figure 3f). If the polarity of the energizing current is periodically changed, the direction of the magnetization in the zone around the small aperture changes and an alternating emf of considerable amplitude appears in the output winding. This condition of the transfluxor is called the open or unblocked condition. Thus, the transfluxor is a gate for alternating currents.

The blocked and unblocked conditions of the transfluxor can be easily characterized by two switching loops: $\Phi = f(I_e)$ as shown in Figure 4a. Loop 1 corresponds to the unblocked position while loop 2 to the blocked. In the unblocked position, the magnetization is reversed in legs 2 and 3 and the energizing current in this case is equal to I_{3-2}; if the transfluxor is blocked, the magnetization must be reversed in legs 3 and 1 and the current is equal to I_{3-1}, corresponding to a spurious unblocking.

The relationship between these currents is called the excitation current margin:

$$K_e = \frac{I_{3-1}}{I_{3-2}}.$$

With the transfluxor unblocked and a sinusoidal energizing current, a high amplitude, distorted emf will be induced in the output winding as the magnetization reversal takes place along loop 1. In the blocked condition

the flux changes only by $\Delta\Phi$, as the energizing current does not exceed the value of I_{3-1}. The output emf is minimum and approximates a sine wave as the magnetic flux changes along the horizontal linear part of the loop. The output emf waveforms for a blocked and unblocked transfluxor are shown in Figure 4b.

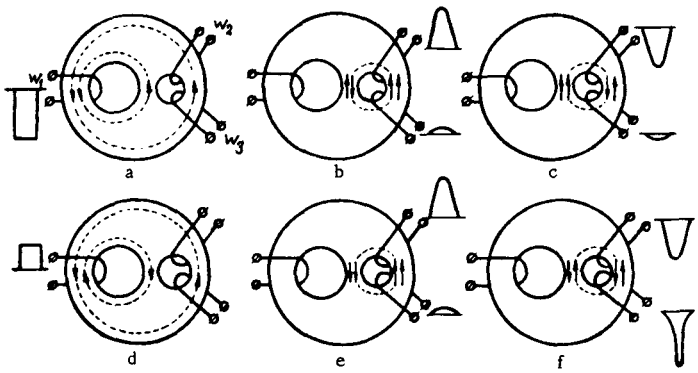

FIGURE 3. Principle of operation of the transfluxor:

a—blocked condition; b and c—energizing and output pulses in the blocked condition; d—unblocked condition; e and f—energizing and output pulses when unblocked. Full arrows show the direction of the control flux; dashed arrows are the energizing fluxes.

One of the drawbacks of operating with a simple transfluxor is that the control and energizing currents must be limited in amplitude. When the control current is too large it is possible that instead of unblocking, a spurious blocking will occur, and when the energizing current is too high, a blocked transfluxor will be spuriously unblocked.

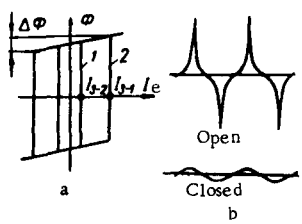

FIGURE 4. Graphs showing the operation of a transfluxor:

a—switching loops; b—output waveforms.

If when unblocking the transfluxor, the control current exceeds the value necessary to reverse the magnetization only of leg 2, then the magnetization in leg 3 will also be reversed. Further increasing the control current will cause the whole core volume to be reversely magnetized, and the

transfluxor will pass into the blocked condition, but with a direction of magnetization opposite to that shown in Figure 3a. Therefore, the control current I_e necessary for unblocking the transfluxor, must be limited in value to

$$I_c = \frac{H_c\, l_{av.b}}{w_1},$$

where $l_{av.b}$ is the average length of the boundary of the zone around the large aperture where the magnetization is reversed, given in meters; H_c is the coercive force for the given core material; and w_1 is the number of turns on the control winding.

If the control current exceeds I_c, then instead of being unblocked, the transfluxor will be blocked, but with its magnetization in the opposite direction. The same effect will occur with large energizing currents.

For normal transfluxor operation it is necessary to reverse the magnetization only in the zone around the small aperture. The peak energizing current necessary to effect this is determined by:

$$I_e = \frac{H_c\, l_{av.s}}{w_2},$$

where $l_{av.s}$ is the average length of the boundary of zone around the small aperture where the magnetization is reversed, given in meters; and w_2 the number of turns of the energizing winding.

If the energizing current exceeds I_e, then the flux set up by the energizing winding can create a magnetizing field equal to H_c for the zone for which $l_{av} = l_2$, and reverse the magnetization of certain parts of leg 1 (Figure 5a). Consequently, the magnetization will be reversed in leg 3 and remain unchanged in leg 2. Therefore, the zone around the small aperture will be primed for the reversal of magnetization under the influence of the energizing current. The transfluxor will be unblocked without any opening action on part of the control pulse.

The property of the simple transfluxor to be spuriously unblocked or blocked with voltage variations is one of its major shortcomings.

When the polarity of the energizing current is as shown in Figure 5b, no spurious unblocking will occur, even if the value of this current is considerable, as the magnetization of the core cannot be changed neither in path 3-2, nor in path 3-1. This phenomenon can be used to increase the energy transfer coefficient from winding w_2 to winding w_3, by using an asymmetric energizing current.

The amplitude of the halfwave of the energizing current, which creates a danger of spurious unblocking, is decreased to I_e, while the amplitude of opposite polarity can be several times higher. Using the large halfwave for driving, and the smaller for priming, the energy transfer factor from winding w_2 to winding w_3 can be increased. The magnitude of the output emf can be controlled, by reversing the magnetization of only part of leg 2. That is to say that the magnetization is reversed only in a certain part of the core around the smaller aperture (Figure 6). By feeding current pulses of different amplitudes to the control winding, the active section of the core along legs 2 and 3 can be changed, and the magnitude of the output emf can be charged.

This characteristic of the transfluxor can be used in devices for memorizing definite signal levels. The fixed level can be stored in the transfluxor almost indefinitely. In addition, this property of the transfluxor enables it to be used as a variable inductor.

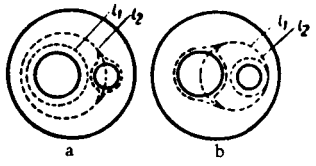

FIGURE 5. Direction of magnetic fluxes for which:

a—a spurious unblocking is possible via path 3—1; b—a spurious unblocking is impossible.

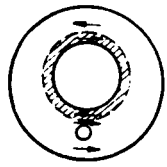

FIGURE 6. Magnetic flux distribution when the magnetization in leg 2 is partially reversed.

The simplest transfluxor has certain advantages over a ring-type ferrite. For instance, readout takes place without disturbing the recorded information. With pulse control, a long signal appears on the output, not a single pulse. The readout and energizing pulses have practically no effect on the input control circuits and, consequently, there is no possibility of feedback from the output to the input. In addition, transfluxor systems require a smaller number of components thus increasing operational reliability.

Main relationships used in transfluxor calculations

When calculating transfluxor circuits, the same relationships are used as for toroidal core circuits /4/. It is assumed that the transfluxors are made of a uniform material in the form of disks and their internal apertures are circles. Consequently, we can assume with a sufficient degree of accuracy that all the lines of force are circles too.

The cross sections of the zones of the magnetic circuit of the transfluxor are different. In a two-apertured transfluxor there are three legs with cross sections s_1, s_2, and s_3 (Figure 1a). Taking into account that the flux is set up by the control winding placed on leg 1, we can write, since the sum of the fluxes is zero,

$$\Phi_1 = \Phi_2 + \Phi_3.$$

The indices correspond to the leg numbers of the magnetic circuit.

For Φ_1, to saturate legs 2 and 3, it is necessary that

$$s_1 \geqslant s_2 + s_3.$$

When the core is fully saturated

$$\Phi_m = B_m s,$$

where B_m is the maximum flux density when the core is saturated; and S is the cross section of the saturated zone.

Knowing the number of turns of the winding placed on any leg, we can determine the induced emf:

$$e = -w \frac{d\Phi}{dt}.$$

The inductance of the winding is determined by:

$$L = \frac{w^2 s}{l} \cdot \frac{B_m}{H_m},$$

where s is the active cross section of leg 3, and l the average length of the flux path in the zone where the magnetization is reversed. The ratio $\frac{B_m}{H_m}$ is called the dynamic magnetic permeability μ_d.

The ampere-turns necessary to reverse the magnetization of a particular zone is determined by

$$Iw = H_c l_{av}.$$

When the width of this zone is small, the average length of the flux path is determined by

$$l_{av} = \pi\left(\frac{d_1 + d_2}{2}\right),$$

where d_1 and d_2 are the maximum and minimum diameters of the magnetization reversal zone.

Materials with hysteresis loops of high rectangularity are used for making transfluxors and can be the same as those used for making ferrite toroidal cores. The rectangularity ratio is defined as the ratio between the residual induction to the maximum induction

$$\kappa_{rec} = \frac{B_r}{B_m}.$$

Materials having a κ_{rec} = 0.9 to 0.97 are used to make transfluxors.

When the cores are operated as memory devices, their quality of operation is characterized by the squareness ratio

$$\kappa_{sq} = \frac{B_{\frac{H_m}{2}}}{B_m},$$

where $B_{\frac{H_m}{2}}$ is the value of induction when the magnetic intensity is $\frac{H_m}{2}$.

The value of κ_{sq} for various materials is different and depends on the form of the transition knee of the hysteresis loop. The sharper the knee, higher κ_{sq}, and the more reliable the element operation.

In calculations it is also necessary to know the switching time of the core, which is defined as the time it takes to reverse the magnetization.

This time depends on the value of the reverse magnetic intensity and is determined either from graphs or from:

$$t_{sw} = \frac{s_w}{H_m - H_c},$$

where s_w is an experimentally determined switching factor for a given material.

When reversing the magnetization of a core by a field whose magnitude is constantly increasing, the area of the hysteresis loop also increases up to a certain limit (limit of the hysteresis loop). The area of the loop remains practically constant when further increasing the magnetic intensity. Therefore for stable operation of the ferrite element, the magnetic field intensity is chosen with a certain margin: $H_m = (5 - 10)H_c$

Determining the geometrical dimensions of two-apertured transfluxors

At present several methods are known for determining the geometrical dimensions of two apertured transfluxors. However, these methods differ from one another, as each was developed for a particular case.

Transfluxors for pulse systems can be designed using a graphical method described in /7/.

The radius of the flux reversal zone is determined by:

$$r = \frac{I_c w}{2\pi H_c},$$

where w is the number of turns of the control winding; H_c is the coercive force of the given material; and I_c the current setting up the coercive force H_c. The radius, r_0, of the large aperture depends on the number of turns of the control winding and the diameter of the wire. The amount of flux that is reversed is given by:

$$\Phi = 2B_m s,$$

where B_m is the saturation flux density of the core, and s the cross section of the flux reversal zone.

The necessary control ampere-turns are determined from the switching diagram (Figure 7). It is assumed that the control winding consists of one wire passing through the center of the large aperture with radius r_0. When the ampere-turns equal Iw_{min}, the magnitude of leg 2 will start reversing; with Iw_{max} ampere-turns it will be completely reversed, corresponding to the unblocked condition of the transfluxor. With Iw_{block} ampere-turns, the magnetization of leg 3 will also be reversed, thus blocking the transfluxor.

Using the same method, the magnetization reversal in the zone around the small aperture of radius r_d can be seen (Figure 7b). The energizing wire passes through the center of the small aperture. With Iw_{min} ampere-turns, the magnetization of the zone around the small aperture commences and is completed with Iw_{max} ampere-turns.

The relationship between all the geometrical dimensions can be determined graphically. For this purpose a graph is constructed showing the

relationship between the ampere-turns and the radius of the magnetization reversal zone for the given material (Figure 8). The ampere-turns corresponding to full and half blocking (x and $\frac{x}{2}$) are marked off on the ordinate. The center of the large aperture is at point *O*. The slope of the function $Iw = f(r)$ depends on the value of the coercive force for the given material and is equal for all zones. Radius r_0 of the large aperture is chosen slightly larger than $r_{\frac{x}{2}}$ for the magnetization not to be reversed in leg 2 by half the control current. The maximum control ampere-turns are determined from r_0. The coordinate of this point on the graph are y, $0.8\,\frac{x}{2}$.

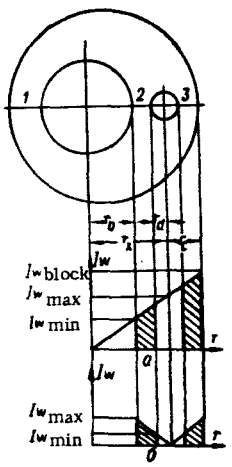

FIGURE 7. Switching diagram:

a—for the zone around the large aperture; b—for the zone around the small aperture.

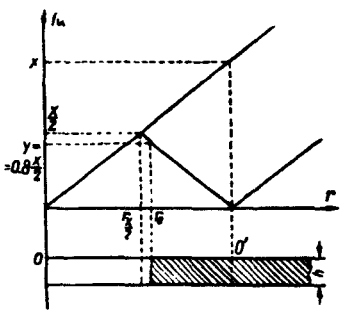

FIGURE 8. Determining the dimensions of the large aperture of the transfluxor.

The thickness of the core is h.

The radius of the small aperture is determined analogously. In the graph, shown in Figure 9, the values of y and $\frac{y}{2}$ are laid off and the value of r_d is determined. The value of r_d is chosen slightly greater than $r_{\frac{y}{2}}$, so as to prevent the magnetization being reversed in the zone around the small aperture by half the energizing current. The design of the other part of the core is shown on the graph.

The advantage of the graphical method is its simplicity and obviousness. The drawbacks of this method are that it is necessary to assume the values of r_0 of the large aperture and the thickness h.

Another method of calculating the geometrical dimensions of a two-apertured transfluxor for memory systems, using the principle of superposition of two currents, was developed at the Institute of Fine-Mechanics

and Computer Technology of the Academy of Sciences of the USSR /1/. All dimensions of the transfluxors in this method are given in reference to the diameter of the large aperture d_1 and the value $n = \frac{D}{d_1}$ (Figure 10).

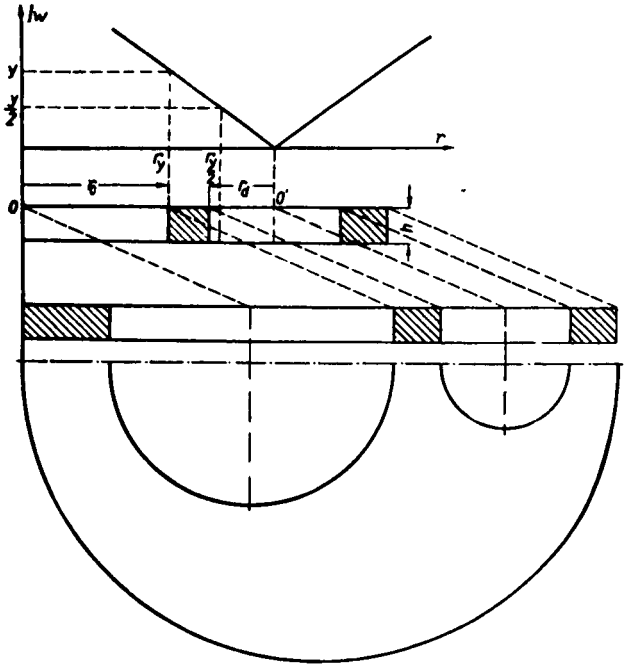

FIGURE 9. Determining the dimensions of the small aperture of a transfluxor.

The external diameter of the transfluxor is given by:

$$D = nd_1.$$

The diameter of the small aperture is

$$d_2 = \frac{n-1}{2n-1} d_1.$$

The width of control leg 1 is:

$$a = \frac{(n-1)^2}{2n-1} d_1.$$

Other dimensions are given by:

$$b = \frac{(n-1)^2}{2(2n-1)} d_1;$$

$$\kappa = \frac{n-1}{2(2n-1)} d_1;$$

$$e = \frac{n^2}{2(2n-1)} d_1.$$

The transfluxors used in automation and telemechanization are of larger dimensions than those used in computer technology. This is because comparatively larger output powers and voltages are necessary, as the output signal of the transfluxor is used to drive semiconductor amplifiers or other elements requiring more power. Thus, when designing transfluxors for automation and telemechanization the output characteristics of the transfluxor are of primary importance.

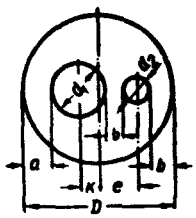

FIGURE 10. Determining the dimensions of a transfluxor by the method developed at the Institute of Fine Mechanics and Computer Technology.

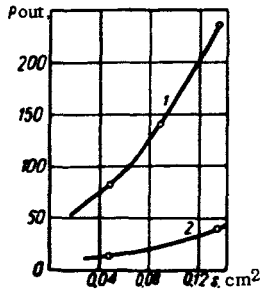

FIGURE 11. The function $P_{out} = \varphi(s_3)$ for a transfluxor of IM-2 material.

The basic data for determining the geometrical dimensions of a two-apertured transfluxor are:

1) the output power;
2) the frequency of the energizing current;
3) the necessary margins for the control and energizing currents.

These calculations should determine: (1) the legs 2 and 3 for the given output power; (2) the diameters of the apertures and the outer diameter of the transfluxor.

The output winding of the transfluxor is placed on leg 2 or 3, the cross sections of these legs being equal.

The output power of the transfluxor, with a given energizing current frequency, depends on the cross section of leg 3. However, we cannot obtain maximum power in the output winding as calculated for the cross section of leg 3. This is explained by the fact that the energizing current must be limited, in order to prevent possible spurious unblocking. As the output power is proportional to the energizing current in the linear part of the magnetization curve, we can write:

$$\frac{P_m}{P_e} = \frac{I_m}{I_e},$$

where P_m is the maximum output power for the given cross section; P_e is the optimum output power with energizing current I_e; I_m is the energizing current for fully saturating legs 2 and 3; and I_e is the energizing current necessary for setting up the magnetic intensity H_e in legs 2 and 3.

The optimum output power from the transfluxor is then:

$$P_e = P_m \frac{I_e}{I_m}.$$

The cross section of leg 3 is best determined from the graph $P_{out} = \varphi(s_3)$ shown in Figure 11. To increase the strength of the core it is necessary to choose $h \geqslant b$. Knowing the cross section of leg 3, we can determine the number of turns of the output winding

$$w_{out} = \frac{U_{out}}{4fs_3B_m},$$

where U_{out} is the necessary output voltage; and f is the energizing current frequency, in cps.

The diameter, d_2, of the small aperture is determined by the cross sections of the windings placed in it. The cross section of each winding is determined by:

$$s = \frac{\pi}{4} \cdot \frac{d_w^2 w}{\kappa_3},$$

where d_w is the diameter of the wire of the winding (from 0.1 to 0.2 mm); and κ_3 the filling coefficient for the given wire (chosen from tables for MARK PEV wires, diameter 0.1, 0.2 mm, κ_3 = 0.1 to 0.2).

The windings are wound on the transfluxor by a special needle, and consequently cannot occupy more than half the area of the aperture with diameter d_2. Therefore, the diameter of the small aperture can be determined by:

$$d_2 = 0.56\sqrt{(1.3-2)s},$$

where s is the sum of the sections of the winding placed in this aperture.

Since the transfluxor may spuriously unblock and block when the control and energizing currents are too high, it is necessary when evaluating the operational reliability, to incorporate margins for these currents. The control current margin is given by:

$$K_c = \frac{I_{c_2}}{I_{c_1}},$$

where I_{c_1} is the control current which, exceeded, causes a spurious blocking of an unblocking transfluxor; and I_{c_2} is the control current fully unblocking the transfluxor.

The margin for the energizing current is determined by:

$$K_e = \frac{I_{e_2}}{I_{e_1}},$$

where I_{e_1} is the energizing current, which when exceeded causes a spurious unblocking of the blocked transfluxor; and I_{e_2} is the energizing current for which the magnetization is completely reversed in the zone around the aperture of diameter d_2.

Let us determine these margins from the core characteristics.

To unblock a blocked transfluxor it is necessary to change the magnetization only around the larger aperture.

The control current to effect this is given by

$$I_{c_1} = \frac{H_c l_1}{w},$$

where

$$l_1 = \pi(d_1 + b).$$

It follows from this that as the control current increases, the zone where the magnetization is reversed also increases. When

$$l_2 = \pi(d_1 + 0.5d_2 + 2b)$$

a spurious blocking of the transfluxor will take place as the magnetization will be reversed not only in leg 2, but also in leg 3 (Figure 12a).

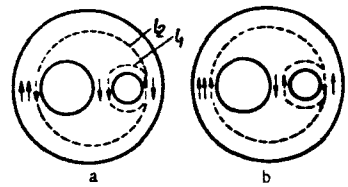

FIGURE 12. Determining the margins:

a—for the control current; b—for the energizing current.

The control current margin can be determined by the ratio between the flux paths:

$$K_c = \frac{l_2}{l_1} = \frac{d_1 + 0.5d_2 + 2b}{d_1 + b}.$$

The same method is used to determine the energizing current margin K_e

The current necessary to reverse the magnetization of the zone around the aperture of diameter d_2 is:

$$I_{e_1} = \frac{H_c l_1}{w},$$

where

$$l_1 = \pi(d_2 + b).$$

With maximum energizing current the magnetization will be reversed not only in leg 2 but also in leg 1 (Figure 12b):

$$l_2 = \pi(d_2 + 0.5d_1 + 1.5b)$$

and the energizing current margin is:

$$K_e = \frac{d_2 + 0.5d_1 + 1.5b}{d_2 + b}.$$

The larger the margin, the larger the supply voltage variations with which the transfluxor can operate. By changing the ratio between d_1 and d_2 we can increase the value of one margin, but invariably the other will be reduced. Therefore, it is necessary to calculate the optimum margins according to the particular design requirements of each case.

It should be shown that K_c can be increased indirectly, e.g., by creating two additional apertures in the magnetic circuit or by placing the unblocking windings on legs 2 or 3. It is more complicated to increase K_e, as this can only be done by changing the ratio between d_1 and d_2. First, d_2 is determined, then d_1. The operational reliability of the transfluxor depends on the choice of d_1, since this determines the value of K_e. Given a definite K_e, we can determine the diameter of the apertures by:

$$d_1 = 2[d_2(K_e - 1) + b(K_e - 1.5)].$$

If $K_e = 1.5$, $d_1 = d_2$.

If for any reason it is necessary to have a definite control current margin, then d_1 can be determined by:

$$d_1 = \frac{b(2 - K_c) + 0.5d_2}{K_c - 1}.$$

The external diameter of the transfluxor core is determined from:

$$D = d_1 + d_2 + 4b.$$

For more stable transfluxor operation, the leg 3 is chosen slightly smaller than leg 2, and leg 1 slightly greater than the sum of legs 2 and 3.

Example. Design a transfluxor for operating in telemechanical systems. The transfluxor drives a P4 transistor. The energizing frequency is 20 kcs. The energizing current margin K_e is 2.

To fully turn on the transistor with a load in the form of a signal lamp, a power of 10 to 15 mW is required. From curve 2 in Figure 11 we determine leg 3; $s_3 = 0.06\ \text{cm}^2$. We take $b = 2$ mm, $h = 3$ mm.

Let us calculate the number of turns of the output winding. The base voltage of the transistor must be around 0.5 v. For reliable transistor switching we choose $U_b = 2$ v. For an IM-2 ferrite, $B_m = 0.18$ webers/m^2, then:

$$w_{out} = \frac{U_b}{4fs_3B_m} = \frac{2}{4 \cdot 20{,}000 \cdot 0.06 \cdot 10^{-4} \cdot 0.18} = 23 \text{ turns}.$$

The number of turns of the energizing winding w_e depends on the characteristics of the energizing source. When the internal resistance of the source $R_s = 5$ Kohm, the number of turns of the energizing winding is 10 to 30. Let us choose $w = 30$. We choose a PEV-2 wire with a diameter of 0.12 mm.

The cross section of the winding is

$$s = \frac{\pi}{4} \cdot \frac{d_w^2(w_{out} + w_e)}{\kappa_3} + \frac{3.14 \cdot (0.12 \cdot 10^{-3})^2(23+30)}{4 \cdot 0.1} = 6.3 \cdot 10^{-6}\ \text{m}^2$$

The diameter of the small aperture is:

$$d_2 = 0.56\sqrt{2s} = 0.56\sqrt{2 \cdot 6.3 \cdot 10^{-6}} = 0.002 \text{ m} = 2 \text{ mm}.$$

The diameter of the large aperture is:

$$d_1 = 2[2(2-1) + 2(2 - 1.5)] = 6 \text{ mm}.$$

The external diameter of the transfluxor is:

$$D = d_1 + d_2 + 4b = 6 + 2 + 6 = 16\,\text{mm}.$$

The control margin for this transfluxor is:

$$K_c = \frac{d_1 + 0.5d_2 + 2b}{d_1 + b} = \frac{6 + 1 + 4}{6 + 2} = 1.35.$$

Transfluxor preparation and grading

The only suitable materials for preparing transfluxors operating with pulses are those having rectangular hysteresis loops. The operational reliability of the transfluxor depends on the degree of rectangularity. It is, therefore, recommended that materials be chosen whose coefficient of rectangularity is not less than 0.9.

Usually transfluxor cores are made from ferrites. The most widely used are magnesium-manganese ferrites $MgO \cdot MnO \cdot Fe_2O_3$. Ferrites do not have a particular direction of easy magnetization and are magnetically isotropic. Therefore the magnetization conditions for all legs of the magnetic circuit are equal.

A high degree of rectangularity of the hysteresis is maintained only for small values of magnetic intensity $H_m = (1 - 4)H_c$. With higher values of magnetic intensity, the rectangularity is decreased due to increasing flux density B_m.

One of the drawbacks of ferrites is their low temperature stability. With increasing ambient temperature, the hysteresis loop is reduced and so is the value of the residual induction.

The ferrite cores are made by pressing. When the geometrical dimensions are calculated, a die is made whose working surfaces are thermally treated, and then polished. For cores of comparatively simple configuration the main parts of the die are made from steel designations U81, U10L, U8, and U10. A die for pressing transfluxors with two apertures is shown in Figure 13.

When designing the die it is necessary to take into account the shrinkage of the material after heat treatment, which is 10 to 15%. This shrinkage depends also on the configuration of the core. The shrinkage of thin walled cores, as a rule, is more than for thickwalled ones.

The cores are pressed with a pressure of 2 tons per cm^2. Before pressing, the powder is mixed with a binding material. Insert (2) is put into form (1). Rods (4) are then placed into the openings of this insert, which correspond to the diameters of the apertures. The form is filled with compound and insert (3) is put in place and pressed. After pressing, the rods are taken out and then inserts (2) and (3) together with the core. The thickness of the core is determined by the quantity of material.

The pressed cores are heat treated at a temperature of 1000 to 1400°C, and then slowly cooled so as to create a uniform structure and to decrease internal stresses. The prepared cores can be polished.

Transfluxor cores are graded by the same method used for common toroidal cores. The main characteristics for choosing the superior cores are the rectangularity ratio and the values of maximum induction and coercive force. These characteristics are determined either by a comparison with a standard core, or by the hysteresis loop. The hysteresis loop is easier to see on an oscilloscope.

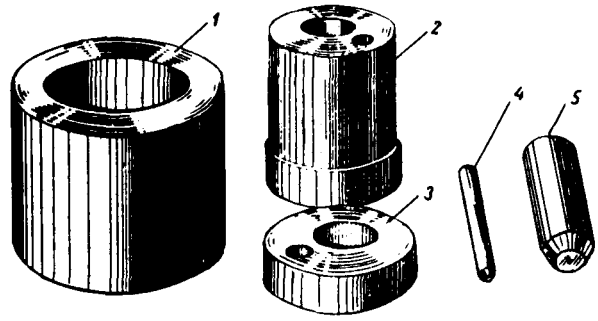

FIGURE 13. A die for a two-apertured core.

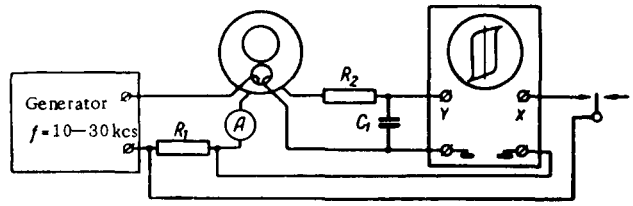

FIGURE 14. Block diagram of an installation for taking off an hysteresis loop.

The most suitable installation for taking off the hysteresis loop is an installation with a switch in the horizontal amplifier. The block diagram of this installation is shown in Figure 14; its main parts consist of a 10 to 20 kcs energizing generator with a high internal resistance, an integrating circuit R_2C_1, and a video amplifier.

Using the oscilloscope scale:

$$B_m = \frac{\sqrt{2}UC_1R_2}{sK},$$

where U is the rms value of the voltage at the output of the integrating circuit; C_1, R_2 are the component values of the integrating circuit; s is the cross section of the core; and K is the gain setting of the amplifier.

Knowing the geometrical dimensions of the core and measuring the core's magnetization current for the limiting hysteresis curve, we can determine the coercive force:

$$H_c = \frac{I}{l},$$

where I is the rms value of current; and l the average length of the flux path.

The maximum magnetic intensity is:

$$H_m = \frac{\sqrt{2}U}{lR_1} ,$$

where R_1 is the resistance connected in series with the primary winding.

By reading from the oscilloscope the values of B_m and B_r we can determine the rectangularity ratio κ_{rec}.

The main characteristics of the ferrites used at present have the following values: B_m = 0.15 to 0.5 weber/m^2; H_c = 8 to 120 ampere-turns/m; κ_{rec} = 0.8 to 0.96.

Chapter II

TRANSFLUXOR CHARACTERISTICS AND CIRCUITS

Transfluxor characteristics

The main characteristics of a two-apertured transfluxor are the control and energizing characteristics.

The control characteristic (Figure 15a) is the relationship between the output a-c emf and the amplitude of the control current. This characteristic can be obtained either by using control current pulses or a current sweep, taking into account the influence of the magnetization by direct current. The influence of the magnetization on the value of the output emf will be less on the increasing part of the curve than on the decreasing slope. This is explained by the fact that on the increasing part of the slope only leg 2 will be magnetized while on the decreasing part, both legs 2 and 3 are magnetized (see Figure 1).

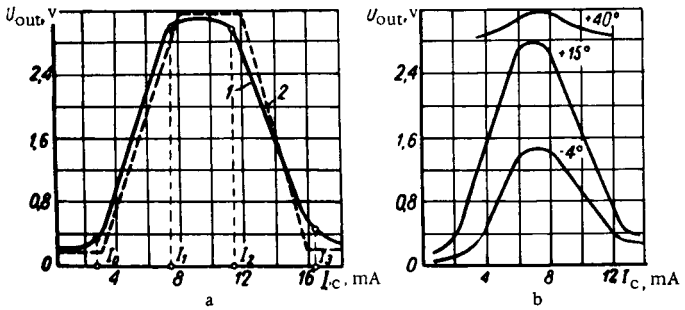

FIGURE 15. Control characteristics:

a—taken at an ambient temperature of 20°C; 1—experimental; 2—calculated; b—taken at different ambient temperatures with I_e constant.

The control characteristic is taken off as follows. The control current required to unblock a blocked transfluxor is gradually increased from zero. The output emf, at first, is equal to a minimum value which is induced due to the nonideal rectangular hysteresis loop. As the control current gradually increases, the magnetization begins to reverse in leg 2, the transfluxor begins to open, and the output emf increases. The output emf will continue to increase until the magnetization of leg 2 is completely reversed. After the transfluxor is fully unblocked, further increasing of the control current

will start magnetization reversal in leg 3 and the output emf will decrease to a minimum value. When the magnetization of leg 3 is fully reversed, the transfluxor is blocked.

Thus, on the control characteristic there are the following points: I_0 - the transflux begins to open; I_1 -fully unblocked; I_2 - begins to close; I_3 - fully blocked.

The width of the peak of the curve depends on the ratio between the diameters of the internal apertures $\frac{d_1}{d_2}$. The larger the ratio, the narrower the peak. When d_1 is very much larger than d_2, point I_1 and I_2 almost coincide.

From the control characteristic we can determine the output voltage ratio κ and the control current margin, K_c:

$$\kappa = \frac{U_{max}}{U_{min}};$$

$$K_c = \frac{I_3}{I_1}.$$

The control characteristic can be constructed analytically. For this, it is necessary to determine the currents I_0, I_1, I_2, I_3, and the voltage U_{max} and U_{min}.

Basically, the control currents are determined by determining the average length of the magnetic paths for each case. A blocked transfluxor starts to open when the control current starts to reverse the magnetization in leg 2. To simplify calculations, the hysteresis loop is assumed to be ideally rectangular and as the control current increases from zero, no change in the magnetization takes place until the knee of the curve is reached.

Only when the magnetic field intensity reaches the value H_c does the magnetization reversal start in leg 2. Therefore, the maximum diameter of the magnetization reversal zone is d_1 and the minimum $d = 0$. The length of the average mmf path is:

$$l_{av} = \pi \frac{d_1}{2},$$

then

$$I_0 = \frac{H_c}{w} \cdot \frac{\pi d_1}{2}.$$

The average mmf path in this case passes inside the aperture of diameter d_1, i.e., through air, as the permeability of the saturated material approximates the permeability of air.

When the magnetization is completely reversed in leg 2, the transfluxor is unblocked. The control current I_1 necessary for full opening is:

$$I_1 = \frac{H_c}{w} \pi(d_1 + b).$$

Blocking begins to take place when

$$I_3 = \frac{H_c}{w} \pi(d_1 + 0.5d_2 + 2b).$$

Full blocking occurs when the magnetization is reversed in all of leg 1.

The blocking current for this is:

$$I_3 = \frac{H_c}{w}\pi(d_1 + d_2 + 2{,}5b).$$

Let us determine the values of U_{max} and U_{min}:

$$U_{max} = 4fws_2\Delta B_{max};$$
$$U_{min} = 4fws_2\Delta B_{min},$$

where

$$\Delta B_{max} = 2B_m;$$
$$\Delta B_{min} = B_m - B_r.$$

The output voltage ratio is:

$$\kappa = \frac{\Delta B_{max}}{\Delta B_{min}} = \frac{2B_m}{B_m - B_r}.$$

An experimental transfluxor has the following characteristics: $D = 17$ mm; $d_1 = 7$ mm, $d_2 = 4$ mm; $b = 1.5$ mm, $h = 5$ mm, $H_c = 30$ ampere-turns/m, $B_r = 0.17$ weber/m^2, $B_m = 0.18$ weber/m^2, $w_c = 100$. From these we determine the following: $I_0 = 3.5$ mA, $I_1 = 8.5$ mA, $I_2 = 12$ mA, $I_3 = 15.5$ mA and the output emf when $f = 20$ kc is: $U_{max} = 3.26$ v, $U_{min} = 0.1$ v, and $\kappa = 32$.

The calculated and experimental characteristics of a transfluxor are shown in Figure 15.

A substantially linear relationship exists between the output voltage and the control current on the positive slope of the control characteristic. This linear section is determined by two points: where the transfluxor begins to open and where it is completely open.

The control current required for full unblocking is fixed for the given transfluxor and is independent of where the control winding is placed on leg 1.

The current required to start opening the transfluxor depends on where the control winding is placed on leg 1. This is because the average mmf path changes for each flux reversal zone. If the control winding on leg 1 is concentrated at the axis of the aperture, then the average mmf path for which flux reversal starts in leg 2 is:

$$l_{av} = \pi\frac{d_1}{2}.$$

If we place the control winding so that it occupies half the perimeter of the aperture with diameter d_1 then the average mmf path is:

$$l_{av} = \frac{3\pi}{4}d_1.$$

When the control winding is uniformly distributed around the aperture, the average mmf path is:

$$l_{av} = \pi d_1.$$

In automation devices the transfluxor is successfully used for storing signal levels. Usually the input signal in this case is converted into control current signals.

To increase the memory range it is necessary to increase the ratio $\frac{I_1}{I_0}$. The highest ratio of these currents with a given geometrical transfluxor configuration is obtained if the control winding is concentrated. The ratio of the currents can be determined by the ratio of the average mmf paths. For complete unblocking the average mmf path is:

$$l_{av} = \pi(d_1 + b)$$

then

$$\frac{I_1}{I_0} = 2 + \frac{2b}{d_1}.$$

The lower memory range is obtained when the control winding is uniformly distributed and is:

$$\frac{I_1}{I_0} = 1 + \frac{b}{d_1}.$$

From the above formulas it can be seen that the memory range can be increased by either increasing b, or decreasing d_1. However, as is already known, decreasing d_1 reduces the energizing current margin K_e.

If the transfluxor is controlled by a varying current, it is necessary to insert a fixed bias in the control circuit, so that the transfluxor is unblocked only by a positive or negative current. The magnitude of the bias is determined by:

$$I_{bias} = I_0 + I_-,$$

where I is the maximum amplitude of the negative control current.

Control current range must be coordinated with the memory range, proceeding from:

$$\frac{I_+}{I_-} \leqslant \frac{I_1}{I_0},$$

where I_+ is the maximum amplitude of the positive control current.

A deviation exists from the control characteristic when the transfluxor is multiply switched by currents of the same value. In experimental tests the deviation from the average value is about ±4%. This deviation is explained by the structure of the core material, i.e., the width of the zone where the flux reversal takes place.

The second important transfluxor characteristic is the driving characteristic, which is the relationship between the output voltage ratio and the energizing current as expressed by $\kappa = \varphi(I_e)$. An experimentally determined driving characteristic is shown in Figure 16. This form reminds us of the control characteristic, as the flux reversal in the zone around the small aperture of diameter d_2 is similar to that in the zone around the large aperture.

As the energizing current increases, and as the transfluxor is periodically unblocked and blocked, the output voltage ratio is zero up to the energizing

current magnitude for which flux reversal occurs in leg 2. The output voltage then continually increases. The minimum output voltage also increases but in smaller amounts up to the moment when spurious unblocking commences. The output voltage ratio thus gradually increases up to a definite limit, until the energizing current reverses the magnetization of all leg 2. This condition corresponds to the maximum output voltage ratio.

If the energizing current is further increased, flux reversal will start in leg 1, causing the output voltage minimum to increase and a fall in the output voltage ratio. With a certain value of energizing current, this ratio will equal zero, the transfluxor will not be able to block, resulting in complete loss of control.

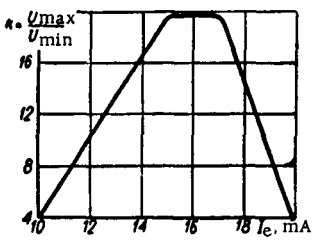

FIGURE 16. Driving characteristic.

It is necessary to select the working point on the positive part of the curve and not to reach the maximum value, since in this case the stability of operation is low.

The shape of the curve depends on the geometrical dimensions of the transfluxor, mainly on the aperture diameter ratio $\frac{d_1}{d_2}$. The higher this ratio, the wider the curve, and the more reliable the operation of the transfluxor.

A strong influence on the shape of the characteristic is exerted by changes in ambient temperature. Control characteristics at different temperatures are shown in Figure 15b. At low temperatures the output voltage is decreased, even though the induction is slightly increased. The coercive force increases even more. Since the increased energizing current does not change its value, the output voltage is decreased.

At higher temperatures the hysteresis loop is narrowed due to the decreasing value of the coercive force, causing a sharp drop in the operational reliability of the transfluxor. With increasing temperature and unvarying energizing current, all control is practically lost, as spurious unblocking occurs.

The characteristics of materials with a high coercive force are affected less by changes in ambient temperature. Thus, for instance, the coercive force of material IM-2 changes by 25 to 30% when the temperature changes by ±60°C, while material IM-1 changes by 15%.

Placing the windings in the magnetic circuits

The operation of the transfluxor depends considerably on how the windings are placed on the different legs of the magnetic circuits.

The blocking winding can be placed only on leg 1, since for blocking it is necessary to create a flux that will saturate all the legs of the magnetic circuit. Therefore, the blocking winding must be placed on the leg with the largest cross section.

The setting (unblocking) winding can be placed on any of the three legs 1, 2, or 3, since for setting the transfluxor it is necessary to change the direction of magnetization only in legs 2 or 3. However, the control currents and the control characteristics do change, depending on which leg the setting winding is placed.

Let us determine the control currents necessary for setting the transfluxor for each alternative of placing the setting winding. It is obvious that when placing the winding on legs 1 or 2, the currents are equal since the average mmf paths are the same for both cases:

$$I_1 = I_2 = \frac{H_c}{w}\pi(d_1 + b).$$

If the winding is placed on leg 3, then the control current will be higher, as the average mmf path is

$$l_{cp} = \pi(d_1 + d_2 + 2b),$$

Consequently, for reversing the magnetization of leg 3 it is necessary to reverse the magnetization in part of the zone of leg 1. The control current is then:

$$I_3 = \frac{H_c}{w}\pi(d_1 + d_2 + 2b).$$

The control characteristic of the transfluxor when the setting winding is placed on leg 1 is shown in Figure 15. From this characteristic we can see that for reliable transfluxor operation the control current must be between the following limits:

$$I_1 < I_c < I_3.$$

When the control current margin is large these limits are narrowed and the operational reliability of the transfluxor becomes low. If, in addition, the influence of temperature on the characteristic is taken into account, it is obviously not effective to place the setting winding on leg 1.

If the setting winding is placed on legs 2 or 3, then the maximum control current is not limited by:

$$I_c > I_3.$$

This is because the winding placed on leg 2 cannot magnetize the legs of the magnetic circuit corresponding to a blocked transfluxor.

When the control pulse operates, the legs of the magnetic circuit are magnetized by direct current. If the setting winding is placed on leg 1, then the control current is limited and will magnetize only leg 2. If this is done, the output voltage is practically unchanged. The transfluxor is set by the leading edge of the control pulse and the setting time depends on the length of this edge and the time of switching over the core.

When placing the control winding on legs 2 or 3 the control currents are chosen with a large margin, therefore both legs 2 and 3 are intensely magnetized. The high magnetizing current prevents the change of flux set up by the energizing winding, and the a-c output voltage can only appear after stopping the control pulse. This will cause the switching* time of the transfluxor to be increased by the length of the control pulse. If the control pulse is rectangular, this time corresponds practically to the length of the pulse.

* By transfluxor switching time we understand the time from the beginning of action of the control pulse up to the moment an a-c output voltage appears on the output winding.

Thus, if it is possible to allow a certain reduction in speed, then the setting winding should be placed on leg 2.

The energizing winding, in principle, can be placed on legs 2 or 3. However, it is quite obvious that it is not feasible to place it on leg 2, as the energizing current margin will not be high. In fact, for the zone around the small aperture the average mmf path is:

$$l_{av} = \pi (d_2 + b).$$

If the energizing winding is placed on leg 2, then the average mmf path for an increasing energizing current, which may cause spurious setting, is:

$$l_{av} = \pi(0.5d_1 + 0.5b) = \pi \frac{d_1 + b}{2},$$

The energizing current margin is:

$$K_{e_2} = \frac{d_1 + b}{2(d_2 + b)}.$$

Comparing the energizing current margins when placing the energizing winding on legs 2 and 3 we obtain the following relationship:

$$K_{e_3} = 1 + K_{e_2}.$$

From this we can deduce that even with a high ratio of $\frac{d_1}{d_2}$, this margin is very small when the energizing winding is placed on leg 2. Therefore, the energizing winding can be placed only on leg 3.

The output winding can be placed on legs 2 or 3. Usually it is placed on leg 3 as in this case it is easier to wind.

A relatively high magnetic coupling exists between the energizing and output windings when they are placed on the same leg. The energizing current frequency is 10 to 100 kc, and at the higher frequencies this magnetic coupling begins to influence considerably the operational reliability of the transfluxor. At higher energizing frequencies, the coupling between the windings is so large that the minimum output voltage is increased in direct proportion to the increase in frequency and the output voltage ratio falls.

When the energizing and output windings were placed on leg 3 of an experimental transfluxor the voltage output ratio was $K = 20$, and with the output winding on leg 2, $K = 30$.

To decrease the magnetic coupling between the windings in a blocked transfluxor it is necessary to place them on different legs of the magnetic circuit, i.e., the output winding must be placed on leg 2.

Summerizing the above, we obtain the following system for winding placement:

Windings	Mounted on leg
Blocking	1
Setting	2
Energizing	3
Output	2

The a-c energizing of transfluxors

The a-c energizing of transfluxors is quite complicated, since a possibility exists of the transfluxor being spuriously set when the energizing current fluctuates. The choice of energizing current waveform is also very important.

Usually toroidal and transfluxor ferrite core circuits are controlled with square wave pulses. Due to the steepness of the front edge of the flux growth in small coils current pulses of considerable amplitudes are obtained without requiring additional pulse amplifiers for transmitting them from one element to another.

In remote-control devices the transfluxor is best used in combination with a semi-conductor amplifier. In this case the energizing source must produce a sinusoidal current, as with this form of current a maximum power is obtained in the load.

It is necessary to have a stable current source for energizing the transfluxor as when many transfluxors are energized from one source, considerable fluctuation in the current will occur due to the input resistance of the energizing circuit changing under setting and blocking conditions. This can result in a spurious setting.

However, when energizing transfluxors from current sources a considerable distortion appears in energizing current waveform, caused by the nonlinearity of the material. The higher the rectangularity of the loop, the greater the distortion. Therefore, with a sinusoidal energization current, sharp current pulses will appear on the output.

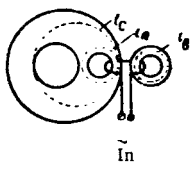

FIGURE 17. Transfluxor core-driving circuit.

When the ambient temperature varies, the characteristics of the material changes, causing unstable transfluxor operation.

These problems are solved by driving the transfluxor with an additional core (Figure 17). In this method the energizing winding encompasses two parallel magnetic circuits, a circuit in leg 3 and a circuit in the driver toroidal core.

Let the designations of the average mmf paths in the transfluxor and the driver core be as follows: l_A—the length of the closed mmf path corresponding to a normally driven transfluxor; l_B—the length of the mmf path of the driver core; l_C—the length of the mmf path corresponding to the spuriously unblocked condition.

The driver core must be made of the same material as the transfluxor core.

The requirements for stable transfluxor operation for the mmf paths in this case are expressed by:

$$l_A < l_B < l_C .$$

Proceeding from these conditions, a suitable diameter of the driver core is chosen. The energizing current must meet the following condition:

$$I_{eB} > I_{cB},$$

where I_{c_B} is the current necessary for setting up the coercive force in the driver core.

From the above formula we can see that by using a driver core the a-c energizing current requirements are independent of the transfluxor dimensions.

Another considerable advantage of using a driver core is that the transfluxor is driven from a voltage source and, hence, a more sinusoidal waveform is induced in the output winding. The output winding may be now heavily loaded.

The full input resistance of the system with a driver core is only slightly changed for an unblocked and blocked transfluxor.

Since the material of both cores are the same, automatic temperature compensation will occur. The transfluxor temperature characteristic, with a current driving source and a driver core are shown in Figure 18a, b. These characteristics are obtained with the input voltage changing between 0.25 to 1 v at a frequency of 20 kc.

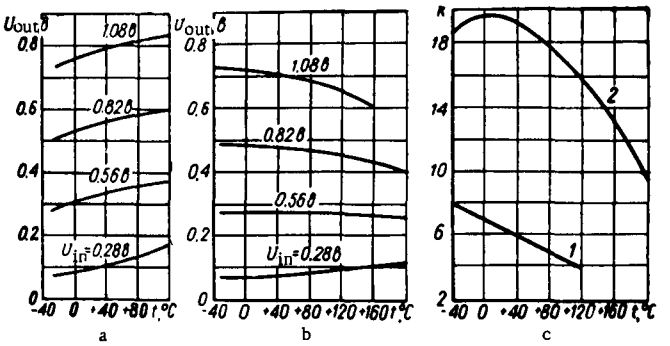

FIGURE 18. Transfluxor temperature characteristic:

a—energization without a driver core; b—energization with a driver core; c—output voltage ratio (1) without driver-core and (2) with driver core.

The additional core also influences the output voltage ratio with change in temperature. The curves in Figure 18c show how the additional excitation core greatly increases the operational stability of the transfluxor as the ambient temperature varies.

Due to the nonideal rectangularity of the hysteresis loop the output voltage ratio is also reduced, as in the blocked condition a certain induced emf still exists and it is usually impossible to obtain a ratio greater than 20. To avoid this drawback, the output emf from a blocked transfluxor is compensated by placing the output winding as shown in Figure 19. This arrangement increases the output voltage ratio to 40. The optimum number of turns of the compensating winding must be chosen for each individual case.

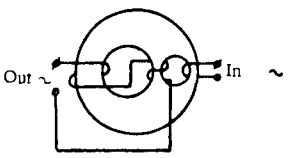

FIGURE 19. Compensated output circuit.

The compensating winding acts on the output emf only when the transfluxor is blocked since then the alternating flux, not being able to change

the magnetic condition of legs 2 and 3, tends to pass through leg 1. When the transfluxor is unblocked, the main flux changes take place in legs 2 and 3 and the flux change in leg 1 becomes small.

As was shown, for the maximum use of legs 2 and 3, asymmetrical energizing currents can be used. However, a great increase in operational reliability cannot be thus achieved, as the amplitude of the smaller halfwave must be limited so as to prevent the possibility of spurious unblocking. The simplest method of generating such a current is to insert in series with the energizing winding a diode and resistor connected in parallel. The positive halfwave passes through the diode, and the negative through the resistor. Thus, the amplitude of one halfwave is limited. It is necessary only to match the polarity of the diode to that of the control pulses.

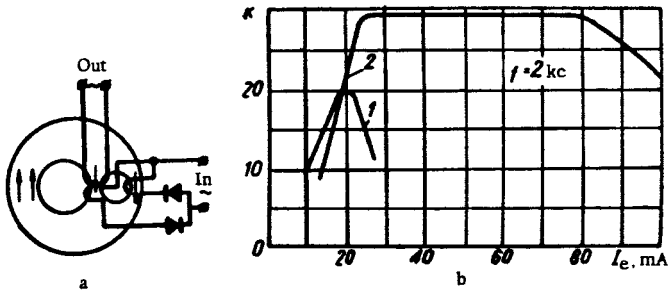

FIGURE 20. Transfluxor with a split energizing winding:

a—circuit; b—driving characteristic: 1—for a normal system; 2—for a system with a split winding.

The direction of the flux set up by the larger halfwave in leg 1 must be in the same direction as the flux set up by the blocking winding. In this case, even with currents of high amplitude, spurious unblocking cannot occur. The amplitude of the smaller halwave must be sufficient only for reversing the magnetization in leg 2.

To increase the energizing current margin by several times, we can split the energizing winding into two equal parts and place them on legs 2 and 3 as shown in Figure 20a. Each half winding is connected through diodes, therefore the energizing current passes alternately through each half winding. The ends of the windings are connected in such a way that when the energizing currents reverse the magnetization around the small aperture, the magnetization corresponding to the blocked condition is simultaneously strengthened. Therefore, any changes in the energizing current do not affect the magnetization of leg 1 and, thus, spurious unblocking is not possible.

The main advantage of this system is that an asymmetrical current generator is not required, and a higher energizing current margin can be had for a given core size. The diodes are placed at the generator output; therefore, a large number of cores can be connected to one source without fear of any variations in the energizing current circuit.

This system has one more important advantage. Since the energizing current is chosen with a large margin, it is possible that spurious unblocking

can occur by a blocking pulse whose polarity is such that it magnetizes the core in a direction opposite to that shown in Figure 20a. Therefore, the unblocking (setting) winding can also be placed on leg 1. In this case the unblocking control current is practically unlimited.

The driving characteristics of the transfluxor when using a sine-wave generator with a normal system and with a system having a split winding are shown in Figure 20b. If we assume a normal output voltage ratio $K = 15$, then for a normal system $K_e = 1.35$ and with a split winding $K_e = 6$.

The output voltage ratio can be increased by using a compensating winding. Thus, for instance, if without a compensating winding the ratio is 10, then with a compensating winding the ratio can be increased to 30. However, the output circuit in this case cannot be heavily loaded as the transfluxor is blocked when a large current flows in the compensating winding placed on leg 1.

The output voltage ratio drops with large energizing current margins. This is explained by the decrease in the coefficient of retangularity of the loop when the magnetic intensity increases. Therefore, it is necessary to determine the relationships between this coefficient and the energizing currents.

Let us determine the rectangularity ratio κ_{rec} when $H_m \approx H_c$.

As is known

$$\kappa_{rec} = \frac{B_r}{B_m}.$$

The value of B_m increases with increasing magnetic intensity. The value of B_r remains constant. Therefore the new rectangularity ratio when the magnetic intensity is H'_m is:

$$\kappa'_{rec} = \frac{B_r}{B'_m}.$$

Let us determine the ratio

$$\frac{H'_m}{H_m} = \frac{B'_m - B_r}{B_m - B_r}.$$

Dividing both the numerator and the denominator of the right-hand side of the equation by B_r we obtain:

$$\frac{H'_m}{H_m} = \frac{\frac{1}{\kappa'_{rec}} - 1}{\frac{1}{\kappa_{rec}} - 1}.$$

From this we get

$$\kappa'_{rec} = \frac{1}{\frac{H'_m}{H_m}\left(\frac{1}{\kappa_{rec}} - 1\right) + 1}.$$

The ratio between the magnetic field intensities can be replaced by the currents ratio, then:

$$\kappa'_{rec} = \frac{1}{\frac{I'_e}{I_e}\left(\frac{1}{\kappa_{rec}} - 1\right) + 1}.$$

We now determine the relationship between the output voltage ratio and rectangularity ratio.

As the amplitude of the output emf depends on the rate of change of the induction, we can determine the output voltage ratio κ by:

$$\kappa = \frac{\Delta B_{max}}{\Delta B_{min}}.$$

When the magnetization of the core is reversed by a-c the induction changes from $-B_m$ to $+B_m$. In the blocked condition, the induction changes from B_m to B_r. Proceeding from the above we can write:

$$\kappa = \frac{2B_m}{B_m - B_r}.$$

Dividing the numerator and the denominator by B_m we obtain:

$$\kappa = \frac{2}{1 - \kappa_{rec}}.$$

Substituting in this formula the rectangularity ratio for the increased energizing current gives:

$$\kappa = \frac{2}{2 - \frac{I'_e}{I_e}\left(\frac{1}{\kappa_{rec}} - 1\right)}.$$

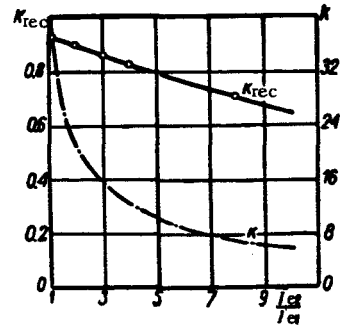

FIGURE 21. The output voltage and rectangularity ratios as a function of the energizing current margin.

The graphs showing the rectangularity and the output voltage ratios as a function of the energizing current margin are shown on Figure 21. From the graphs it can be seen that at first, when doubling the driving current,

the output voltage ratio drops by half and then drops only slightly as the driving current is further increased.

Therefore, to provide a more operationally stable transfluxor it is necessary to choose materials with a higher rectangularity ratio.

If a maximum output voltage ratio is not required then, in the system using a split energizing winding, the driving current can be increased several times.

Transfluxor-transistor circuits

In remote control systems, the transfluxor must provide an output power of the order of several watts. Therefore, the output power from the transfluxor must be amplified. Consequently, the main element when building a remote control system must be a circuit consisting of a transfluxor and a transistor. The transistor operates as a class A amplifier. In order to smooth the d-c component, the load is shunted by a capacitor of 0.5 to 2 μF. The circuit is shown in Figure 22a.

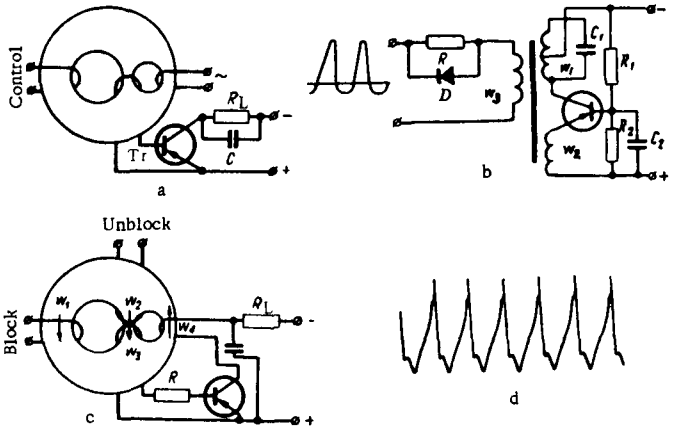

FIGURE 22. Diagram:

a—transfluxor circuit with amplifier; b—asymmetrical energizing generator; c—transfluxor circuit with relaxation oscillator; d—output voltage waveform.

In its operation the circuit is similar to a trigger made of semiconductor elements, but differing in its simplicity, the presence of only one transistor, the absence of additional components and, furthermore, in the blocked condition it does not use energy.

From this basic circuit, a different circuit can be built for use in remote control. With these it is possible to reduce the weight, dimensions, and the energy consumption of the device and to increase operational reliability.

In transfluxor-transistor systems it is necessary to observe the polarity of all windings, as the wrong polarity can reverse the function of operation of the setting and blocking windings, and can alter the current waveform in the output winding.

When feeding to the control winding current pulses of different amplitudes, the magnitude of the d-c current in the load can be changed, which cannot be done, for instance, in trigger circuits. However, this has its own drawbacks, for if the supply voltage varies, there can be several intermediate stable conditions in addition to the two normal ones. Therefore it is necessary to choose the control current with a large margin.

When the transfluxor is blocked, the transistor is cut-off and only a no-load current flows, whose magnitude depends on the degree of rectangularity of the hysteresis loop. It is practically impossible to reduce this current to zero. Therefore the unblock-to-block load voltage ratio is only about 10 to 15.

Transistorized sine-wave generators are used for the a-c drive of transfluxors. The circuit diagram of one such generator is shown in Figure 22b. The generator is very simple and reliable in operation. The coils of the generator are placed on an SB-5 core model; a P4 transistor is used for amplification.

The internal resistance of the generator must be comparatively high (1 to 3 Kohm), to reduce variations in driving current. Without additional amplification, the output of one such generator can be connected to five transfluxors whose energizing windings are connected in series. The number of turns of the energizing winding must be small (10 to 30), for if it is too great, the output voltage ratio will drop considerably. Therefore, the energizing generator must operate into a low ohmic load and be a current source.

If a large number of transfluxors are connected to the generator it is necessary to add a power amplifier and to stabilize the output current. This complicates the device. The transfluxors can also be energized with square waves, but this complicates the generator circuitry, and the efficiency of the transfluxor is lowered.

The circuit, consisting of resistor R and diode D, shapes the asymmetrical current waveform. The positive halfwave is used for driving, and it must create the flux around the small opening in such a direction as not to cause the blocked transfluxor to be spuriously unblocked. The negative halfwave is used for priming and its amplitude is limited to avoid spurious unblocking.

The operating range of the generator is chosen between 10 to 20 kc though transfluxors remain operational up to frequencies of the order of 200 kc. This upper frequency limit is set by the low frequency limit of power transistors and the increasing losses in the generator and the transfluxor cores. At frequencies below 10 kc, dimensions of the cores must be increased to obtain the necessary output power.

To decrease the dimensions of the core and the number of turns, the energizing current frequency must be increased. However, above 50 kc coupling action begins to take place between the energizing and output windings. Due to this influence, the minimum output a-c voltage increases with a blocked transfluxor, causing a drop in the output voltage ratio.

If, for some reason, energizing currents of a higher frequency must be used, then the energizing winding should be placed as far as possible from the output winding so as to avoid direct transmission of energy from the energizing winding to the output winding without any flux reversal taking place.

In practice the energizing and the output windings are placed on different legs of the magnetic circuit. Hence, when the frequency is 20 kc and both

windings are placed on leg 3 a maximum output voltage ratio of $\kappa = 20$ is obtained. When the energizing winding is placed on leg 3 and the output winding on leg 2 the ratio is $\kappa = 30$.

The energizing windings are usually connected in series between the transfluxor. The inductance of the input circuit of the blocked and unblocked transfluxors are different. Therefore, when the transfluxors are unblocked and blocked, the amplitude of the energizing current change considerably. As a result of such changes, spurious unblocking of the blocked transfluxor can take place. To decrease these variations an additional resistor is connected in series with the energizing circuit.

All the disadvantages associated with transfluxor-transistor systems energized from an external generator are removed if we build a system incorporating a relaxation-oscillator. The energizing winding, the output winding, and the amplifier make up a relaxation system (Figure 22c), whose oscillations can be controlled by the transfluxor's operating characteristics. In the blocked condition there is no transmission of energy in the magnetic circuit around the small aperture, the coupling between the windings is negligible and no oscillations occur. In the unblocked condition, the coupling between the windings becomes large and oscillations take place.

The processes taking place in this circuit are the same as those in a blocking oscillator with certain differences. These differences are conditioned basically by the high rectangularity of the hysteresis loop of the core material. If the transfluxor is unblocked, oscillations may not take place when the supply voltage is switched on. This depends on the condition of magnetization in the zone around the small aperture. Therefore the directions of the fluxes set up by the transfluxor windings must be strictly coordinated. The waveform of the generated oscillations is also different from that of a blocking generator: there is no feedback and the waveform is not rectangular.

The collector winding w_4 for reversing the magnetization of the zone around the small aperture is placed on leg 3. The base winding w_3 is placed on leg 2 so as to reduce the magnetic coupling between windings; the blocking winding w_1 is placed on leg 1 and the setting winding w_2 can be placed either on leg 2 or on leg 3. When the setting winding is placed on leg 2, the unblocking sensitivity increases.

The direction of fluxes set up by the windings are shown in the figure. The direction of the flux set up by the blocking winding is the same as that set up by the collector winding w_4. Consequently, there is no possibility of spurious unblocking, as the transistor amplifies in one direction only and leg 3 will be even more saturated.

When a d-c pulse is applied to setting winding w_2, the system starts to oscillate. The waveform of the generated pulses is shown in Figure 22d. The steps on the curve are due to magnetization reversal in the core. The negative halfwave is limited by the transistor being cut-off. The oscillations take place due to the energy storage in winding w_4.

To compensate for the spread in the characteristics of the cores and transistors, an additional resistor is connected into the base circuit, while the number of turns of the base winding is given a certain margin. A system with matched characteristics operates stably over a wide range of supply voltage variations ($\pm 30\%$), but is very sensitive to increasing ambient temperature increases, the coercive force is reduced, making it impossible to block the transfluxor and to stop the oscillations (as the temperature

increases, the blocking ampere-turns increases, while the unblocking ampere-turns decreases).

The rectangularity ratio in the system plays no part, as in the blocked condition when there are no oscillations the current in the load is practically nil and no noise signal exists. Consequently, the cores now need not be selected according to their rectangularity ratio.

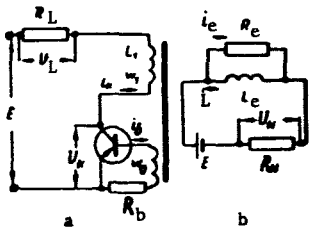

FIGURE 23. Relaxation oscillator: a—circuit; b—equivalent.

The system with the relaxation oscillator has only two stable states and a definite threshold of operation. Generation can either take place with a gradually increasing control or with a current pulse. The operating threshold is determined by the point on the control characteristic where the transfluxor starts to unblock. Therefore, the setting current in this system is several times less than in the usual system used.

The transfluxor with the relaxation oscillator can be used as a control pulse generator and as a switching element. The absence of a special energizing generator, no current in the load in the blocked condition, increased sensitivity, insensitivity to changes in supply voltage, and the simplicity of the system demonstrates the wide possibilities of using this system in automation and telemechanical devices.

The calculations for this generator are similar to those used for a half-wave convertor, working in the no-load conditions, since in this system there is no output winding and the load is connected directly into the collector circuit. It should be taken into account that loads of the order of tens of Kohm should be avoided, since with these too large a voltage drop occurs across the collector in the oscillation condition and when interrupting the oscillations. To obtain a stipulated collector current with a high ohmic load it is necessary to increase the supply voltage. When interrupting the oscillations almost the whole supply voltage appears across the collector and may cause a breakthrough between the emitter and collector.

Since the oscillations in the system are caused by the oscillations of the energy stored in winding w_4, the analysis of the oscillator is the same as for a ringing choke convertor /2/. The processes taking place in the oscillator are quite complicated. Therefore, to simplify the analysis the following assumptions are made:

1. the inductance of the collector winding w_4 is constant;
2. the coupling coefficient between the collector and base windings is equal to unity;
3. the capacitance between coils of the windings is equal to zero.

The equation for the oscillator circuit shown in Figure 23a is:

$$L_1 \frac{di_к}{dt} - M_{01} \frac{di_б}{dt} = E - (U_к + U_L), \qquad (1)$$

where M_{01} is the mutual inductance between windings w_1 and w_0; E is the supply voltage; $U_к$ is the collector voltage; U_L is the voltage across the load; $i_к$ is the collector current; and $i_б$ is the base current.

Since the coupling coefficient between the windings is equal to 1, the voltage across the collector winding is given by:

$$E - (U_к + U_L) = w_1 \frac{d\Phi}{dt}. \qquad (2)$$

The voltage across w_0 is

$$U_o = w_o \frac{d\Phi}{dt}, \tag{3}$$

or

$$U_o = \frac{w_0}{w_1}[E - (U_к + U_L)]. \tag{4}$$

Equation (1) can be rewritten in the form:

$$L_1 \frac{d}{dt}\left(i_к - \frac{M_{01}}{L_1} i_b\right) = E - (U_к + U_L). \tag{5}$$

Knowing that

$$\frac{M_{01}}{L_1} = \frac{w_0}{w_1},$$

we can write

$$L_1 \frac{d}{dt}\left(i_к - \frac{w_0}{w_1} i_b\right) = E - (U_к + U_L). \tag{6}$$

The base current is:

$$i_b = \frac{U_0}{R_b} = \frac{w_0}{w_1} \cdot \frac{E - (U_к + U_L)}{R_b}. \tag{7}$$

Substituting the value for the base current into equation (6) gives the final equation of the oscillator:

$$L_1 \frac{d}{dt}\left[i_к - \left(\frac{w_0}{w_1}\right)^2 \frac{E - (U_к + U_L)}{R_b}\right] = E - (U_к + U_L), \tag{8}$$

or

$$\frac{di_к}{dt} + \frac{1}{\left(\frac{w_1}{w_0}\right)^2 R_b} \cdot \frac{d(U_к + U_L)}{dt} - \frac{E - (U_к + U_L)}{L_1} = 0. \tag{9}$$

This equation is nonlinear due to the nonlinear relationship between the transistor currents and voltages.

The oscillator circuit can be substituted by the equivalent circuit shown in Figure 23b. For this circuit the following equations hold:

$$L_e \frac{di_L}{dt} = E - (U_к + U_L) = E - U_N; \tag{10}$$

$$i_N = \varphi(U_к) = i_L + i_e = i_L + \frac{E - U_N}{R_b}. \tag{11}$$

After differentiation:

$$\frac{di_L}{dt} = \frac{d}{dt}\varphi(U_k) + \frac{1}{R_e} \cdot \frac{dU_N}{dt}. \tag{12}$$

Substituting the value of the derivative into equation (10) we have:

$$\frac{d}{dt}\varphi(U_k) + \frac{1}{R_e} \cdot \frac{dU_N}{dt} - \frac{E - U_N}{L_e} = 0. \tag{13}$$

This equation is analogous to equation (9). Comparing them we can establish that the current as a function of the voltage U_k can be seen as a volt-ampere characteristic of a nonlinear element R:

$$i_N = \varphi(U_k) = i_k. \tag{14}$$

Similarly we can establish that

$$\left(\frac{w_1}{w_0}\right)^2 R_e = R_e$$

and

$$L_1 = L_e.$$

For the oscillator to be a relaxation oscillator the volt-ampere characteristic must have a negative section.

Figure 24 shows the voltages U_{w_1} and U_{w_0} as a function of the supply voltage U_n. These graphs are analogous to the volt-ampere characteristics.

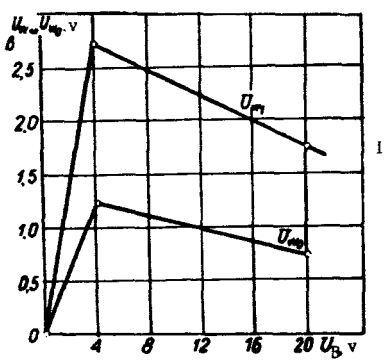

FIGURE 24. Voltage U_{w_1} and U_{w_0} as a function of the supply voltage U_B.

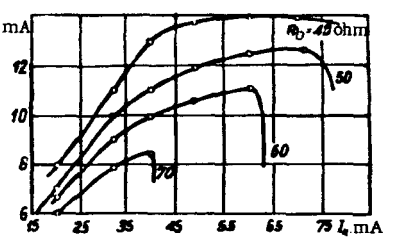

FIGURE 25. The base current as a function of the collector current with different resistors R_b.

The relationship between the base current and the collector current for different resistors R_6 are shown in Figure 25. With small collector currents oscillations cannot start, as the base current is inadequate for turning on the transistor. As the collector current increases the base current initially rises, then falls. The oscillator operates stably when the base current is at its maximum value.

The limits of stable operation depend on the values of R_b. For $R_b = 0$ and an adequate number of turns on w_0, oscillations cannot be interrupted due to spurious unblocking of the transfluxor by a reverse current pulse. For high values of R_b it will be impossible to create relaxation conditions, since the base current is very small.

In each particular case the value of R_b is chosen according to the characteristics of the transistor. From Figure 25 it can be seen that the best results are obtained when $R_b = 40$ ohm, as in this case stable oscillator operation is maintained over a wide range of collector currents and, consequently, over a wide range of collector voltages.

Oscillator stability hardly depends upon any change in the load resistance. In practical circuits, stable operation was maintained when the load resistance was changed from zero to 2 Kohm. The collector current of a P4 transistor changes with this from 10 to 88 mA. It should be noted that the noncritical character of the circuit to any change in the blocking and unblocking currents has been chosen with a margin of 2 to 3. The setting winding can also be placed on leg 1. In this case even with large values of setting current, when the magnetization around the small aperture is reversed, the system still does not begin to oscillate when a spurious unblocking occurs.

The oscillator frequency depends on the source voltage and the load resistance:

$$f = \frac{E - (U_K + U_D)}{4B_m S_\delta w_1}.$$

The optimum turns ratio

$$\frac{w_1}{w_0} = 2 - 5.$$

Technical data of the oscillator: $w_1 = 100$, $w_0 = 30$, $R = 40$ to 100 ohm, P4 transistor.

Chapter III

TRANSFLUXOR APPLICATIONS

Transfluxors in computer technology

The transfluxor as an element with two stable conditions can be used to create different devices for use in computer technology. The simple two-apertured transfluxor can be used to build registers, memory devices, and gates. With three and multi-aperture transfluxors different logic systems can be built.

High-speed memory devices, made of magnetic elements, are widely used in computers. Such a device designed with two-apertured transfluxors is shown in Figure 26. The write address lines pass through the large apertures and envelop legs 1 of each transfluxor. The read-address lines pass through the small apertures and envelop legs 3. Write-in and read-out take place when pulses are fed at the same time on the vertical and horizontal lines. The selected transfluxor goes over to the set condition under the action of the total magnetic flux, set up by the write windings. When read-out takes place, an emf is generated in the output winding.

The advantage of the transfluxor as a memory device is that the recorded information is not destroyed when it is being read down and, furthermore, it is possible to read down from several transfluxors at the same time.

A diodeless shift register, made of two-apertured transfluxors, is shown in Figure 27. Two cores are used for each stage. The transfluxors are directly connected, and the shift signal is amplified by the appropriate choice of the number of turns on the windings. Usually the driven winding has twice less turns than the driving one. The other windings have the same number of turns and form a conductor passing through the apertures.

Initially, all the transfluxors are blocked. When storing a zero the transfluxors are also blocked. Let the number to be stored, e.g., 1010011, be fed to the input winding of the register. At the same time, advance pulses I_3 are fed to windings w_1 of the even cores and to windings w_3 of the odd cores. Windings w_3 serve to block any change of magnetization in leg 3 when recording a 1. When advance pulses are absent, pulses I_1 are fed for advancing information from the odd cores to the even ones. Current pulses I_5 are priming pulses for preparing the shifting of information from one core to the other.

The storing and shifting of a 1 in the register is as follows. A current pulse representing a 1 is fed to the input winding. At the same time a current pulse is fed to blocking winding w_3, which blocks any change of magnetization in leg 3. In the output winding w_4 of the first core no emf is induced and no energy is fed to the second core. The priming current pulse I_5 changes the magnetization in the zone around the small aperture of the first core, and an emf will be induced in the output winding w_4. The polarity

of the induced emf is such that the second core, under the action of the winding w_2, becomes more saturated.

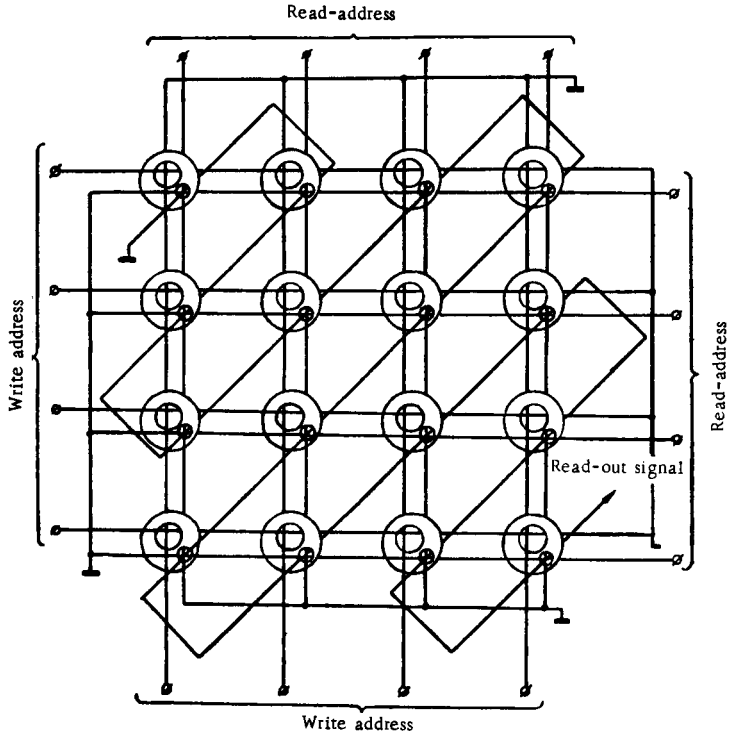

FIGURE 26. Array of transfluxors used as a memory device.

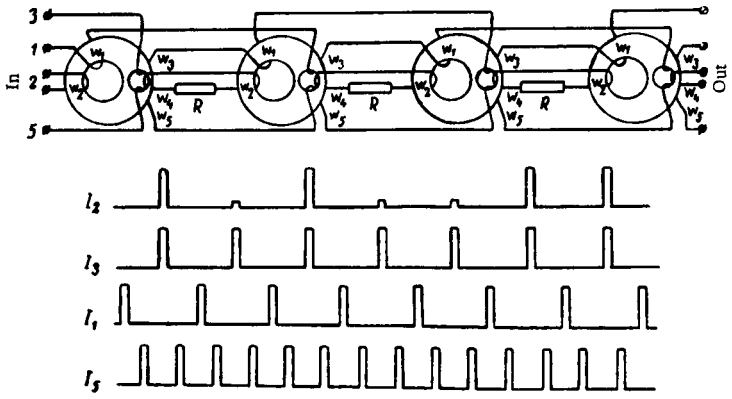

FIGURE 27. Transfluxor shift register.

The advance current pulse I_1 clears the first core to its initial condition, i.e., blocks it. This causes a flux reversal in leg 3 which induces an emf in output winding w_4 of such polarity that the flux is changed in the second core and it is unblocked, i.e., the second core is set to 1. The current pulse I_1 fed to the blocking winding of the second core prevents an emf from being induced in the output winding. After priming the second core, the advance pulse transfers the 1 to the next core.

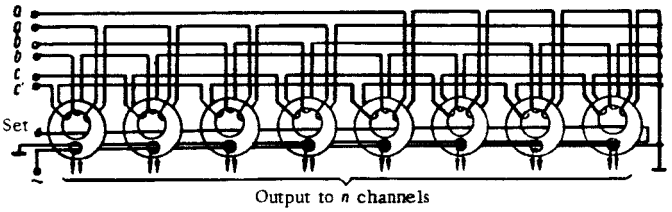

FIGURE 28. Channel selector system.

A diodeless selector system can be built of transfluxors as shown in Figure 28. The selector selects one of n channels in response to a certain binary code at the input. The windings connected to the input terminals are placed on legs 1 of each transfluxor and are used for blocking. The setting windings of all the transfluxors are connected in series and placed on leg 2. Current pulses representing a 1 or 0 are fed to the input terminal pairs aa', bb', cc'. For every combination of pulses, one transfluxor will not be blocked and when a setting pulse is fed into the setting circuit only this transfluxor will be set, and an emf will be induced in its output winding. If, now, another pulse combination appears at the input, the transfluxor previously selected will be blocked and another selected.

Two-apertured transfluxors can be used to make a digital-to-analog convertor as shown in Figure 29. The code-input terminals are enegized by binary code pulses so that the presence of a pulse sets the particular transfluxor. In the output windings of the set transfluxors emf's are induced whose amplitudes are added, since the output windings are connected in series. Thus, a voltage appears at the output whose amplitude depends on the input code. The output signal persists even when the binary code pulses are no longer present. Therefore, before sending a new code a reset pulse must be applied resetting all the transfluxors back to the blocked condition.

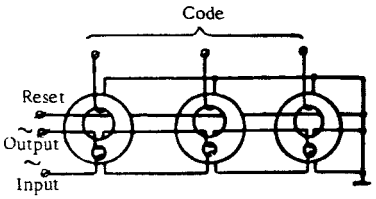

FIGURE 29. Digital-to analag convertor.

Transfluxors in current-steering systems

Circuits, consisting of cores with rectangular hysteresis loop, have a comparatively high resistance before being switched and a low resistance consisting basically of the ohmic resistance of the windings after being switched. This characteristic can be used to build current-steering systems.

In /3/ switches are described consisting of several parallel circuits, each circuit being made up of two ferrite elements. To choose a particular output circuit, a flux reversal takes place in a ferrite of each pair. The read-down pulse from the supply source passes through the circuit with the lowest resistance, i.e., through circuits where flux reversal took place in the ferrites. A comparatively large current flows in the selected output circuit. The main advantage of this method is that the output current is determined primarily by the current from the head-down supply source and not on the characteristics of the selective circuit. Furthermore, this system uses less components than other comparable systems. Certain authors consider the current-steering method as the most applicable when designing devices consisting of magnetic elements.

Current steering can also be used if transfluxors are used as selective elements. This is possible since the input resistance of the driving circuit of the transfluxor changes in the set and blocked conditions. The advantage of the transfluxor over the torroidal core lies in that for steering circuits diodes are not required, since the controlled pulse is not fed to the output winding when the transfluxor is set.

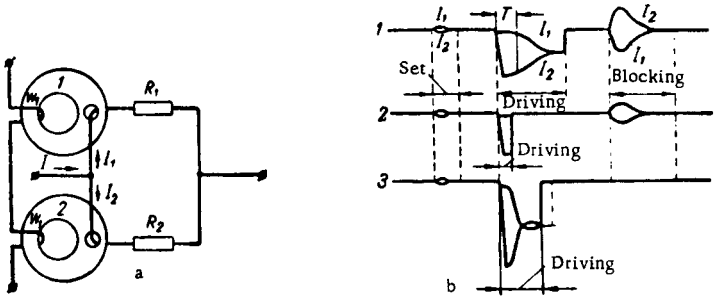

FIGURE 30. Current transmission through two parallel transfluxor circuits: a—circuit diagram; b—current waveforms across loads.

Let us discuss a current steering circuit using two transfluxors, connected together by a selective loop (Figure 30a). Initially, both transfluxors are blocked; windings w_1 are the blocking windings. Current I divides equally between load resistors R_1 and R_2. If one of the transfluxors is set, the drive current divides into two unequal parts. The larger current passes through the circuit of the blocked transfluxor and the smaller through the set one. The amplitude difference between these currents depends on the load resistance and decreases with large load resistances. The amplitude and shape of the branch currents as a function of time for different drive currents are shown by the oscillograms in Figure 30b for three different cases.

In the first case the duration of the driving pulse is longer than the switching time of the core. Let us assume, for instance, that transfluxor 1 is set and 2 is blocked. Then when flux reversal commences around the small aperture of transfluxor 1, the reactance of the drive winding is added to resistance R_1 and the branch current is reduced. The branch current in transfluxor 2 drops considerably* and the difference between the branch currents is considerable. After the flux reversal around the small aperture of transfluxor 1 is complete, the currents become equal. After the next blocking pulse is applied to both transfluxors, equal currents branch current will flow.

In the second case, the amplitude of the driving pulse is the same as in the first case, but its length is equal to the switching time of the zone around the small aperture of the set transfluxor.

In the third case the amplitude of the driving current is so large that the blocked transfluxor may be spuriously unblocked. When this happens, I_1 becomes larger than I_2. Increasing the amplitude of the driving current increases the operating speed of the system, however this will cause the blocked transfluxor to be spuriously unblocked with consequent destruction of the previously recorded information.

To increase the difference between the branch currents, it is necessary to increase the inductance of the winding. Good results are also obtained by splitting the driving winding and placing it on legs 2 and 3 and not only on leg 3 thus reducing the danger of spurious unblocking.

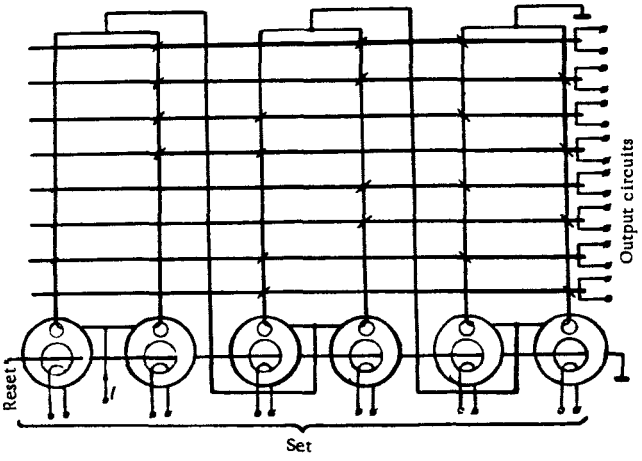

FIGURE 31. A current-steering transfluxor-decoder.

A current-steering transfluxor decoder is shown in Figure 31. One transfluxor of each pair is set depending on the input code; the other transfluxors remain blocked. The first two pairs select, while the third pair inhibits. The driving current sets up a resultant mmf acting only on the selected core, as all the other cores are inhibited. An emf will be

* [The original reads "remains large" but this does not agree with the figure. See article by Rajchman and Crane "Current Steering in Magnetic Circuits".—IRE Trans. on Electronic Computers, pp. 21-30. March 1957.]

induced in the output winding of the selected core. In this decoder, the transfluxor operates in the spuriously unblocked condition, which has a certain advantage. The driving pulse is of sufficient intensity that after selecting the appropriate core, it divides into two equal parts in each transfluxor pair spuriously unblocking them, thus leaving them all in the same state. In addition, it creates a common inhibiting mmf on all output cores. Thus the selected core is reset and the system automatically prepared for operation.

The transfluxor decoder has a higher operating speed than similar toroidal core-diode decoders. The complete selection and reset cycle of this decoder is about 2 μsec.

Current-steering systems are very small, lightweight, and require a small amount of energy. An advantage of these systems is that the characteristics of the elements of the system have no influence on the transmitted current waveform. This is especially important when steering currents represent continuous information. When using transfluxors in steering systems, it is possible to design circuits without any additional components, thus increasing system reliability and speed.

Transfluxors in automation

Practical circuits utilizing transfluxors for storing memory levels of the controlled signal are given in /8/. In this reference a device is described controlling an electroluminescent display. The principal problem which had to be solved in this case was to obtain an a-c output voltage of considerable magnitude (about 100 v) from the transfluxor.

Considerably large output voltages can be obtained with comparatively small transfluxors and a small number of turns on the output winding if square wave driving pulses are used. However, the power required for flux reversal also increases. As has been stated, the energizing current frequency can be increased, but this causes the output voltage ratio to drop. This, however, does not affect the operation of the system as the electroluminescent lamp has a definite firing voltage. A ratio of 3 to 5 is adequate.

The property of the transfluxor that its output voltage can be varied by varying the amplitude of the control current is used to build an electroluminescent display panel.

The panel consists of an array of luminescent lamps connected into horizontal and vertical rows as shown in Figure 32. The transfluxors are controlled by vertical and horizontal gates. The total flux set up by the control windings open the selected transfluxor. The output voltage and, consequently, the brightness of the lamp depends on the magnitude of the control flux. The energizing generator generates an asymmetrical current waveform with a positive to negative amplitude ratio of about 3 to 1. The number of elements in the panel is 1200. When a gating system similar to television scanning systems is used, a moving image can be obtained on the panel.

If a letter or digital display is required, the setting windings should be connected in a certain order so that the lamps should set up the characters required.

The positive part of the transfluxor control characteristic is sufficiently linear. Using this part of the characteristic, we can build memory systems

for varying input signal amplitudes. The advantage of the transfluxor for memorizing level is the persistence of the output signal with pulse action on the input. Such systems can be widely used in automatic devices (correlators, on-off controllers).

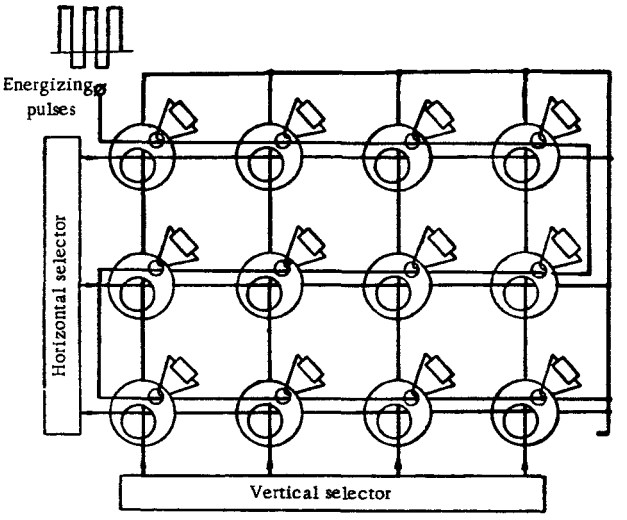

FIGURE 32. Automatic control system for luminescent lamps.

Before recording a new level, it is necessary to reset the previously stored level. A transfluxor memory system for storing levels is shown in Figure 33a. The transfluxor has four windings: a write winding w_1, a reset winding w_2, a drive winding w_3, and an output winding w_4. The varying input signal is the source of supply for transistor T_1. Resistor R_1 is used for establishing the memory range limit.

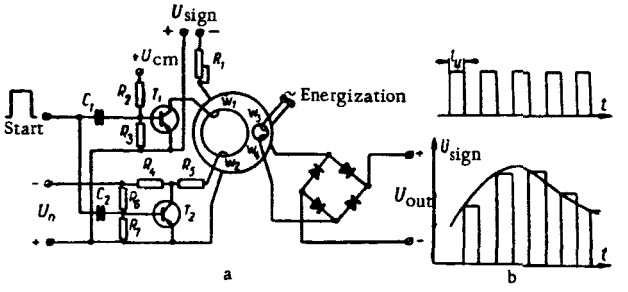

FIGURE 33. Memory system for different input signal levels.

Initially, T_1, is biased off by resistor R_2, while transistor T_2 is turned on by a negative potential set up by divider R_6–R_7. Under this condition w_2 is shunted by T_2. The differentiating circuits C_1, R_3 and C_2, R_7 are for shaping

the start pulse. The leading edge of a square wave pulse cuts off T_2 via the differentiating circuit, causing a current to flow through w_2, blocking the transfluxor thus resetting it. The current flowing is determined by voltage U_n and resistors R_4, R_5. The trading edge of the pulse opens T_1, and the new input signal is recorded. The recorded signal level is converted to a d-c level in the output.

The a-c energizing source must have a stabilized amplitude.

The frequency of operation and output voltage can be increased if the energizing frequency is increased. However, at higher frequencies, the output voltage ratio decreases as the minimum output voltage increases. Therefore the energizing frequency is chosen between 20 to 30 kc.

The amplitude of the output voltage varies with constant input signal amplitude and fixed start signal time. The magnitude of this deviation from the mean value depends on the structure of the core material and the slope of the linear part of the control characteristic. The interval between recording and resetting is fully determined by the length of the square-wave pulse.

The circuit shown in Figure 33a quantizes a continuous signal according to level. Several such circuits, controlled by pulses shifted by equal intervals, are sufficient for this purpose.

Such devices can be used in self-adjusting simulators. Let us take for example a standard signal of a simulator given by a series of standard pulses. Let us quantize the output signal of a real system and compare the pulses for the same period of time. The difference in areas of these pulses is the operating information for self-adjustment. The fact that the length of the quantizing pulse is controllable is an additional arrangement whereby the system can be adapted to different input signal shapes. For example, there is no need to have many pulses of small duration for slowly changing signals and vice versa. The input signal characteristic can be always determined by differentiation, and the length and frequency of the controlled pulses can be set in accordance with the information received.

Experience in using transfluxors in automation systems and especially in self-adjusting systems is still limited. However, even the preliminary results obtained with test objects are satisfactory.

Transfluxors in remote-control devices

In recent years most of the remote control systems developed were made with contactless switching elements such as used in computer technology. The transfluxor, as a switching element with two stable conditions, will find its use in telemechanical systems.

The transfluxor is most suitable for use in output stages, decoders, distributors, coincidence circuits, and in other similar circuits. For instance, the simpler two-apertured transfluxor can well replace magnetic amplifiers operating as relays. Their use makes the devices more simplified, smaller, and faster in operation. The adjustment of transfluxor devices is much simpler than those using magnetic amplifiers.

In most cases the transfluxors can replace transistor triggers. The number of components is considerably reduced. In devices with a large number of transfluxors, a relaxation oscillator system is recommended.

A decoder circuit with a frequency coded remote control system with parallel coding, using transfluxors in the output circuits, is shown in Figure 34. The diode matrix is controlled by transistors T_1 and, when no signal is present at the frequency filters, are cut off by the negative bias set up by resistors R_3. The control windings w_1 and w_2 of the transfluxors are switched to the supply source via the series-connected resistors R_1 and R_2. The ratio between the values of these resistors influences the ratio between the control current and the no-load current. The magnitude of the allowable no-load current is chosen according to the transfluxor control characteristic and should not exceed the threshold of operation. The control current margin must not be less than 2.

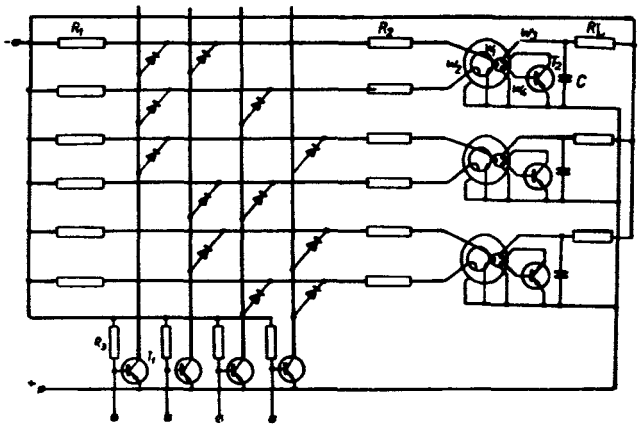

FIGURE 34. A decoder system with transfluxors in the output circuits.

Initially, the diodes of the matrix shunt the input circuits of the transfluxors and pass only no-load current. When a decoded binary signal appears at the input, the corresponding transistors are cut-off and one of the control circuits of the decoder passes current through the winding of the selected transfluxor. This current is a series of pulses, as both diodes of the matrix can only be simultaneously cut-off when two frequencies are in phase.

Windings w_1 and w_2 are, respectively, the unblocking and blocking windings. The selected transfluxor will be either unblocked or blocked, depending on the winding through which the control pulses pass. The oscillator starts to act on the unblocked transfluxor via windings w_3 and w_4 and a d-c current flows through the load R_L. The load resistance R_L and capacitor C are a decoupling filter for decoupling the supply circuit from the oscillator pulses acting on the control circuit and to prevent spurious energizing when peaks appear on the supply voltage.

When the load consists of signal lamps and the transfluxor is fed from an external energizing generator, the voltage across the load in the blocked and unblocked condition are, respectively, 2.3 and 24 v, and with the same load and and using a self-energizing system, 0.2 and 24 v. The no-load currents in the control windings is 1 mA for each transfluxor, while the working control current is 20 mA.

To insure a certain group transmission sequence in sequential signalling, distributors are necessary. A contactless distributor system using transfluxors, developed for these circuits, is shown in Figure 35.

The main element of the distributor is the trigger which uses a transfluxor as a control and memory device. The distributor is switched at a frequency set by pulse generator GI. Windings w_1 and w_2 are, respectively, the unblocking and blocking windings. The loads of transistors $T_1 - T_4$ are generators GCh_1 to GCh_4. To set the distributor to zero an additional blocking winding, not shown, is placed on each transfluxor.

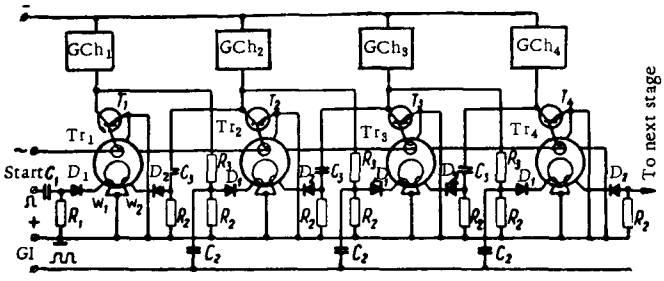

FIGURE 35. A transfluxor-distributor system.

Initially, all the transfluxors are blocked and the generators voltage is practically nil.

The distributor is started by feeding a positive pulse to the "start" terminals, which is applied via capacitor C_1 and diode D_1 to the unblocking winding w_1 of transfluxor Tr_1. Pulses from generator GI are not transmitted to the unblocking windings of transfluxors T_2 to T_4 since diode D_1 is cut off by the voltage set up by voltage-divider R_3, R_2, when the transistors are cut-off. When transfluxor Tr_1 operates, T_1 is turned on and generator GCh_1 is connected to the supply. A voltage is set up across divider R_3, R_2, opening diode D_1 and a transfer pulse from generator GI is fed via capacitor C_2 and diode D_1 to the unblocking winding of transfluxor Tr_2. Transistor T_2 conducts and generator GCh_2 is connected to the supply and at the same time pulses are fed via capacitor C_3 and diode D_2 to the blocking winding w_2 of transfluxor Tr_1. The supply to generator GCh_1 is cut off and transfluxor Tr_3 is primed for operation. The further stages of the distributor operate similarly. When the circuit is closed in a loop we get a ring counter.

The main advantage of this distributor in comparison with transistor-distributors is that only one transistor is used per stage, the simplicity of the system, and the comparatively small number of components.

The a-c energization can be obtained from an external generator or from relaxation oscillators.

Another interesting distributor system uses toroidal cores with transfluxors in the output circuit. This system has the positive qualities of both elements. A toroidal-core distributor with two-cycle switching has a minimum number of components, very small dimensions, and very high speed. However, this distributor cannot be always utilized, as only a single pulse occurs in the load circuit. If a transfluxor is inserted into each output circuit, we obtain a distributor in which the output signal

persists up to the switching time of the next circuit, or till the whole system is reset. An a-c output signal can be obtained if there is no rectification or amplification, or a d-c signal if a transistor is connected in the output of the transfluxor.

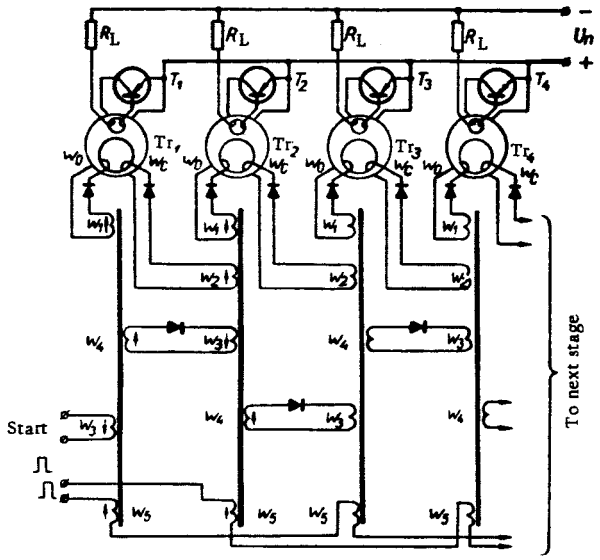

FIGURE 36. A ferrite-core distributor system with output to transfluxors.

Figure 36 shows a distributor system with transfluxors in the output circuits. The transfluxors are energized by relaxation oscillators. Initially, all the transfluxors are blocked and no-load currents flow in the transistor loads R_L. The flux in all the ferrites is in the upward direction therefore the driving pulses fed to windings w_5 bring about no flux change in the ferrites. When a "start" pulse is applied, flux reversal takes place in the first ferrite inducing a pulse in winding w_1, unblocking transfluxor Tr_1 via winding w_0.

The oscillator of transfluxor Tr_1 operates and a nominal current passes through the load. Winding w_4 of the first ferrite primes the second ferrite for operation via winding w_3. A driving pulse brings about a flux reversal in the second ferrite, resets the first transfluxor via winding w_c, turns off the oscillator of Tr_1 and turns on the oscillator of Tr_2. The next circuits operate similarly.

The main advantage of the system described is in the small number of components per stage. A distributor with a transfluxor output functions the same as a distributor made of transistors but with approximately half as many components per stage.

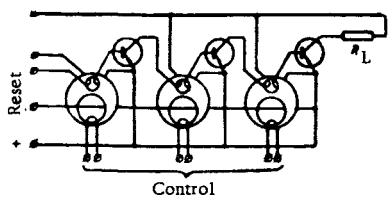

FIGURE 37. A coincidence circuit with an unlimited number of inputs.

By placing the unblocking and resetting windings of the transfluxors on designated ferrites, we can obtain a device generating a preset series of pulses, differing in length.

By using transfluxors, it is easy to build a coincidence system with an unlimited number of inputs as shown in Figure 37. The control pulses at the input can arrive, not only at the same time, but in any sequence, since each signal appearing is fixed by a separate transfluxor.

The blocking windings are connected in series. A reset pulse brings all the transfluxors into the blocked condition and the system is prepared for operation. The energizing generator is switched to the energizing winding of the first transfluxor. The transistor of each circuit is loaded by the energizing winding of the next circuit. The output signal is taken off the collector of the transistor of the last circuit and is available only when a control signal has been present at all the inputs.

The transistors generate an asymmetrical energizing waveform for the subsequent circuit. The output signal lasts until the system is reset.

Multi-apertured transfluxors

Multi-apertured transfluxors were developed comparatively recently and are used in different automation devices and in computing technology. A four-apertured transfluxor has the same functions as one with two apertures, but has several advantages.

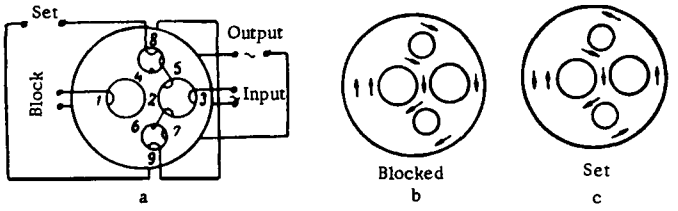

FIGURE 38. Four-apertured transfluxor.

A four-apertured transfluxor can operate as a switching device at ambient temperatures ranging from -50 to +180°C without special temperature compensation arrangements.

Six-apertured transfluxors, called logicors, can perform complicated logic operations, such as numerical half-addition and add-parity checking. One such element can replace 12 transistors in a logic circuit /6/.

Figure 38 shows a transfluxor with four aperatures. Two additional apertures create a magnetic circuit with 9 zones through which the magnetic flux branches and flux reversals can take place.

The windings of a four-apertured core can be placed as in the two-apertured transfluxor. The advantage of the four aperture design in this case lies in the fact that the length of the magnetic path is increased for spurious blocking and setting. When the transfluxor is set, path 1-4-2-6-1 remains magnetized, and the magnetization is reversed in leg 3 by the magnetic flux changing in path 1-8-3-9-1. This route is much longer than the route 1-4-2-6-1. The margin can thus be increased by about 50%.

If we use separate windings for blocking and setting and place them as shown in Figure 38a, then the control margin is practically unlimited. The transfluxor is blocked by saturating the parallel flux paths 1-4-2-6-1 and 1-8-3-9-1, using the blocking winding (Figure 38b). The magnetization of legs 2 and 3 are in the same direction. The setting windings are placed on legs 8 and 9 and are connected in series in such a way that the fluxes in legs 8 and 9 are in the same direction. The direction of the setting flux must be opposite to that of the blocking flux. The setting flux can pass only along path 1-8-3-9-1 as shown in Figure 38c. Thus the control current must satisfy the following requirements:

$$I_B > I_C\, I_S > I_0$$

where I_B is the blocking current; I_S is the setting current; and I_C is the current required to reverse the flux in a particular zone.

The maximum control current is not limited, therefore the control margin and consequently the operational reliability of the transfluxor is practically unlimited.

Since separate control windings are used, the transfluxor can be controlled by pulses of either polarity. The a-c output winding is placed on legs 5 and 7, thus fully isolating the output from the action on part of the control pulses.

A four-apertured transfluxor, as an element with two stable conditions, can be used for building logic systems. An OR circuit with two inputs is shown in Figure 39.

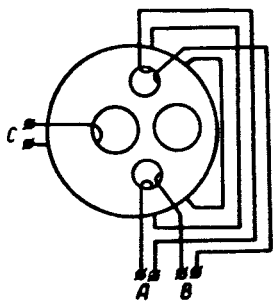

FIGURE 39. A transfluxor OR circuit.

To increase the number of inputs it is necessary to add the appropriate number of windings. An output signal appears when a control signal is fed to input a or b or to a and b simultaneously. The output signal will persist until a reset signal is applied at input c.

This system can be used as an AND circuit if the control currents fed to inputs a and b are limited to the values given by equations:

$$0.5 I_{1,8,3,9} < I_A < I_{1,8,3,9};$$

$$0.5 I_{1,8,3,9} < I_B < I_{1,8,3,9}.$$

Each current by itself cannot change the magnetic condition of path 1-8-3-9-1, and the transfluxor can be only set by the sum of the currents.

A three-apertured transfluxor used as an AND circuit is shown in Figure 40. This circuit differs from the former in that an output signal appears only when a control signal is fed first to input *A* and then to input *B*.

A magnetic circuit with three apertures is divided into four legs. Initially, the transfluxor is blocked by feeding a reset current pulse to the "reset" winding. The configuration of the magnetic fluxes is illustrated in Figures 40a, b, and c. A control pulse applied to input *A* will cause a flux reversal in leg 2. The amplitude of the pulse applied to input *A* must be

limited to such a value as will not affect a flux reversal in legs 3 and 4. After a pulse has been applied to input *A*, the picture of the magnetic fluxes is as shown in Figure 40b. The fluxes in legs 3 and 4 are still in opposite directions and there is no output signal. The magnetization in legs 2 and 3 is changed by a control pulse applied to input *B*. The control pulse must be limited in amplitude in order not to change the condition of leg 4. The picture of fluxes in this case is as shown in Figure 40c. The direction of the fluxes in legs 3 and 4 are the same and an a-c driving current will induce an emf in the output winding.

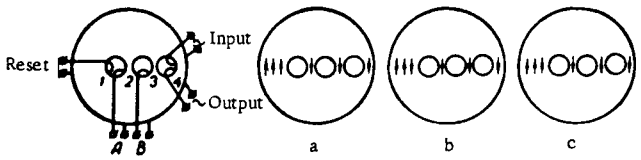

FIGURE 40. A three-apertured transfluxor AND circuit.

When the control pulse sequence is reversed, no output signal appears due to the amplitude limitation placed on the control currents.

For the normal operation of the three-apertured transfluxor, the following requirement must be met:

$$s_1 = s_2 + s_3 + s_4.$$

An OR circuit designed of a three-apertured transfluxor is shown in Figure 41.

The circuit is reset by a reset pulse which sets up flux paths as shown in Figure 41a. Since the fluxes around the central aperture are in counter-rotational directions, no a-c signal can be transmitted. A control pulse at either input *A* or input *B* will reverse either flux around the central aperture, setting up conditions for an output signal to appear. The directions of the magnetic fluxes in this condition are shown in Figure 41b.

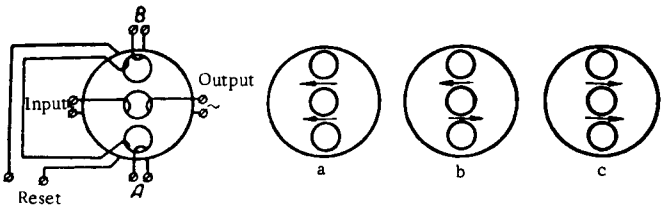

FIGURE 41. A three-apertured transfluxor OR circuit.

If the control pulses are applied at the same time at both inputs *A* and *B*, both fluxes change their direction around the central aperture and are again in opposite directions, and the transfluxor remains blocked. The direction of the magnetic fluxes is shown in Figure 41c.

A more complicated transfluxor design is a logic element with four inputs. This element consists of a disk with six apertures in which windings are placed as shown in Figure 42. This element can be used to solve such logic operations as odd-parity pulses applied to inputs *A*, *B*, *C*, and *D*.

The a-c output winding consists of two parts placed on different legs of the magnetic circuit and connected in series in such a way that the signals induced in both halves of the windings are cancelled with the result that an output signal will appear only when one side of the transfluxor is unblocked.

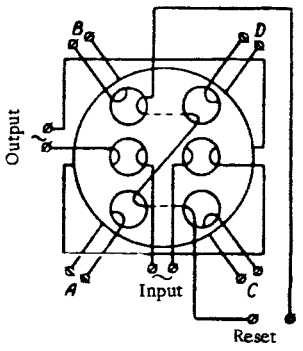

FIGURE 42. Six-apertured transfluxor with four inputs.

Figure 43a shows the flux distribution of a transfluxor blocked by a reset pulse. A control pulse applied to input *A* changes the direction of the flux around aperture *a*, unblocking the left-hand side of the transfluxor so that an a-c output signals is generated. The flux distribution in this case is shown in Figure 43b. A control pulse at input *C* changes the direction of the flux around aperture *c*, unblocking the right-hand side of the transfluxor and an a-c output signal is generated. The flux distribution for this case is shown in Figure 43c.

A control signal at input *D* changes the direction of the flux around aperture *d*, unblocking the left-half of the transfluxor (Figure 43d), and an a-c output signal is generated. A control signal at input *B* blocks the transfluxor.

Analyzing the system, we can establish that the transfluxor is unblocked only when an odd number of signals is applied and blocked with an even number of signals. The logical block-diagram of a six-apertured transfluxor with four inputs is shown in Figure 43e.

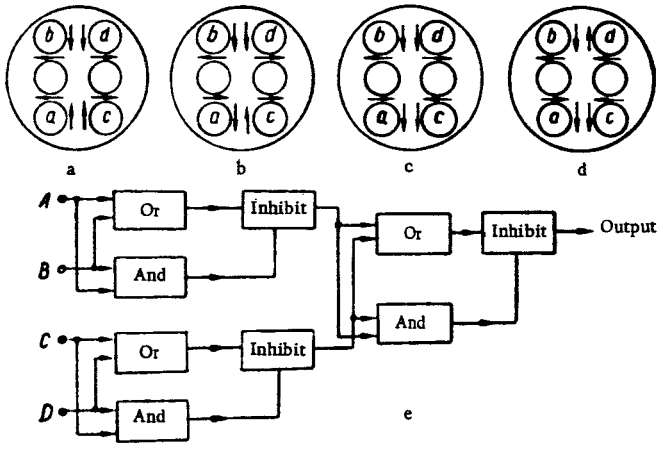

FIGURE 43. Flux states and logical block diagram of a six-apertured transfluxor.

All control currents must be limited in amplitude in order to avoid flux reversal in neighboring legs of the magnetic circuit.

A six-apertured transfluxor can be used for selecting channels controlled by binary code. The a-c output signal appears only after a desired one of four possible binary codes appears at inputs A, B, C, and D.

The winding configuration for code 11 is shown in Figure 44. The reset and output windings are placed in the same way as in the odd-parity checker. A control pulse at input A changes the direction of the fluxes around apertures a and c opening both halves of the transfluxor but, due to the cancelling action of the output winding, no output signal is generated. A control pulse only on input B will reblock the right-hand side of the transfluxor so that there is once again no a-c output signal. However, if control signals are applied at both inputs A and B in any time sequence an a-c output signal appears, since the left-hand side of the transfluxor is unblocked and the right-hand side remains blocked and the total current in the output winding is not equal to zero.

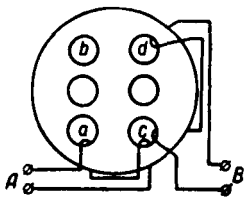

FIGURE 44. Winding configuration for code 11.

By appropriate placement of the control windings we can build systems for codes 01, 10, and 00.

Selective transfluxors may be directly cascaded by connecting the a-c output of one transfluxor to the a-c input of the next. Thus, if an N call channel is required, the number of selective transfluxors m required is:

$$m = \frac{\log_2 N}{2}.$$

Another type of transfluxor or switch*, shown in Figure 45a, is a toroidal ferrite with many apertures. The number of apertures must be even and their diameters equal. The condition for normal switch operation is:

$$b \geqslant 2a.$$

The number of a-c outputs is equal to the number of aperture pairs. The control windings are placed in the odd apertures and the a-c windings in the even ones. The initial flux directions are shown in Figure 45b. The direction of the fluxes around aperture 2 are in opposite directions and therefore the a-c current, fed to the driving winding, cannot reverse the direction of the magnetization around this aperture. Consequently, no a-c current flows in the output winding.

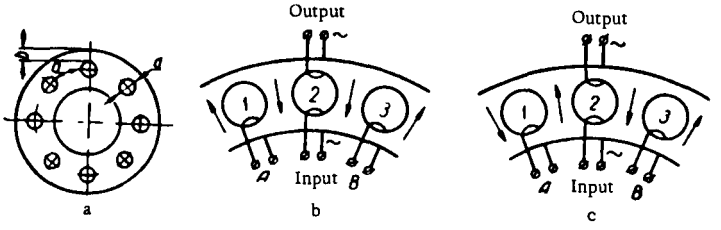

FIGURE 45. Transfluxor switch.

* Developed by A.D. Ryabinin and D.M. Shkvar.

A control pulse at input A reverses the flux around aperture 1, as a result of which the direction of the fluxes around aperture 2 will now be in the same direction and an a-c signal may be generated in the output winding. A control pulse at input B reverses the fluxes around aperture 3, as a result of which the direction of the fluxes around aperture 2 will be again in opposite directions and the transmission of an a-c signal around aperture 2 to the output winding will be blocked. An a-c signal can be induced in the output winding placed in aperture 4.

The amplitude of the emf (in volts) induced in the output winding is:

$$U_{out} = \frac{s w_{out} \Delta B}{T},$$

where s is the area of the irregular section of zone with diameter $d + 2a$, in m^2; T is the energizing current period, in sec, and ΔB is the change of induction when flux reversal takes place:

$$\Delta B = 2Br.$$

As in the previously described multi-apertured cores the control and energizing pulses must have limited amplitude. The advantages of these switches is their simplicity of manufacture, small number of components, and small weight and dimensions. When using compensating cores in the energizing circuits the switch can operate at temperatures up to +200°C. More complicated transfluxor circuits have been designed. These are usually used for solving logic problems. Multi-apertured cores in the form of rectangular plates with many windows can be used as memory devices. The advantage of such devices consist in that their geometrical dimensions are minimum, as the windings are placed by a metalization process.

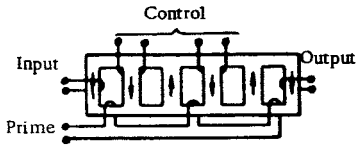

FIGURE 46. Laddic core AND system.

A logical AND unit with several inputs can be designed of laddic cores as shown in Figure 46. The principle of operation of the system is as follows. The input winding is placed on the first rung of the core, and the output winding on the last. The number of rungs must be even. The output signal is obtained only when the flux set up by the input winding cannot pass through any of the intermediate rungs. This is achieved by setting up blocking currents with the control windings placed on the even rungs. If even one of the control pulses is absent, the flux set up by the input winding passes through the shorter path via the unblocked rung and no emf is induced in the output winding. The magnetization in the odd rungs is in the same direction as the flux set up by the input signal; therefore the energizing flux paths cannot close through them. To reset the system, a pulse is applied to the prime winding.

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